AGN feedback and galaxy evolution

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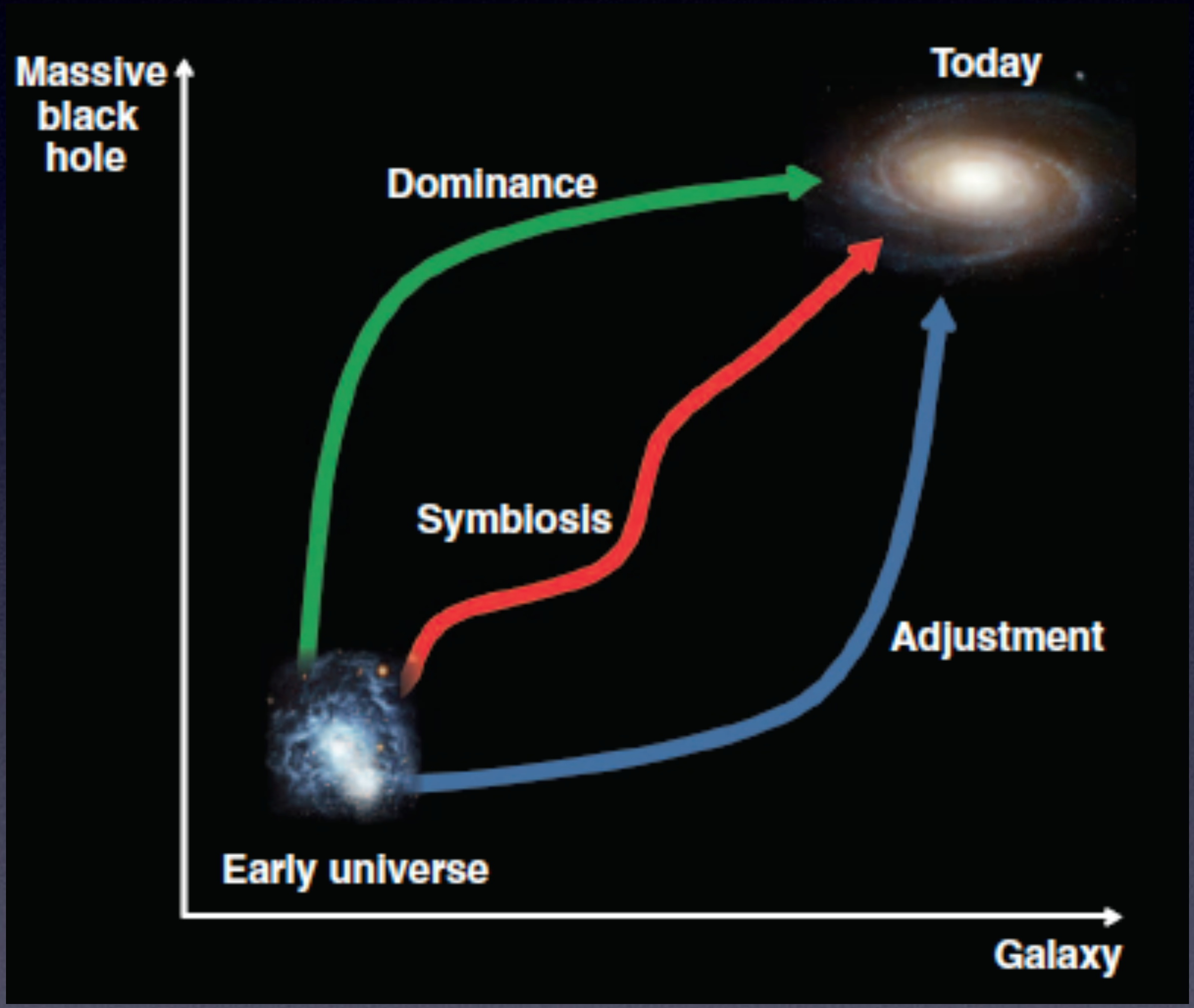
Outline:
- AGN-galaxy co-evolution through feedback: results
- perspectives from ground and space
- NOEMA : next Iram array

Galaxy - Massive Black Hole evolution

Through which path does the common growth occur?



Volonteri 2012, Science

- Merging
  - Galaxy
  - MBH
    - accretion
- Feedback
  - Stellar / SN
  - AGN

The merging sequence

Two Spirals

The Antennae

NGC 6240

Elliptical Galaxy

Merging nuclear supermassive BHs

When galaxies merge their
nuclear MBHs also merge

Menci et al. 2003:

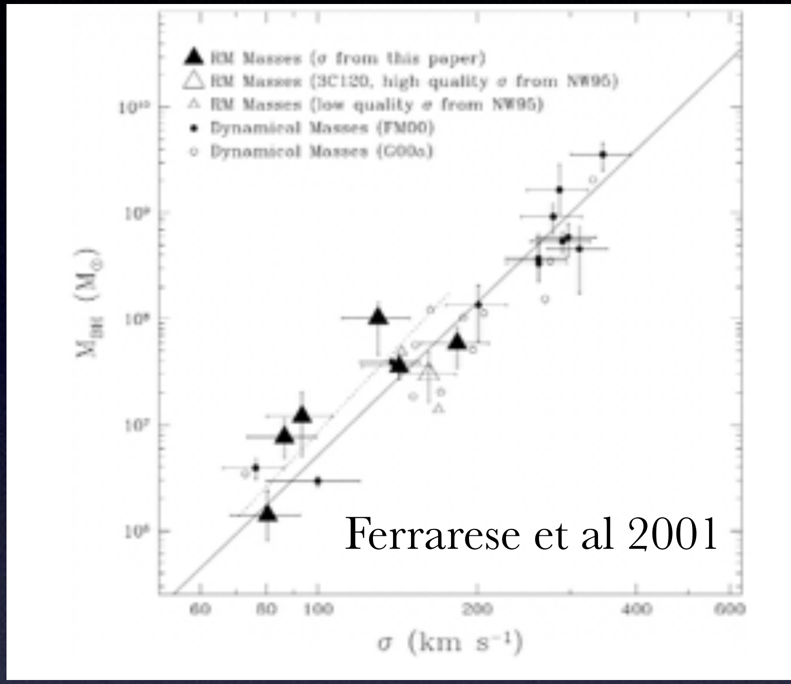
- **merging histories of the DM clumps imply that Mgas ~$\sigma^{2.5}$**
- **destabilization of Mgas by interactions steepens by another σ**
- **SN feedback depletes the residual gas shallow potential wells, further steepening the correlation.**

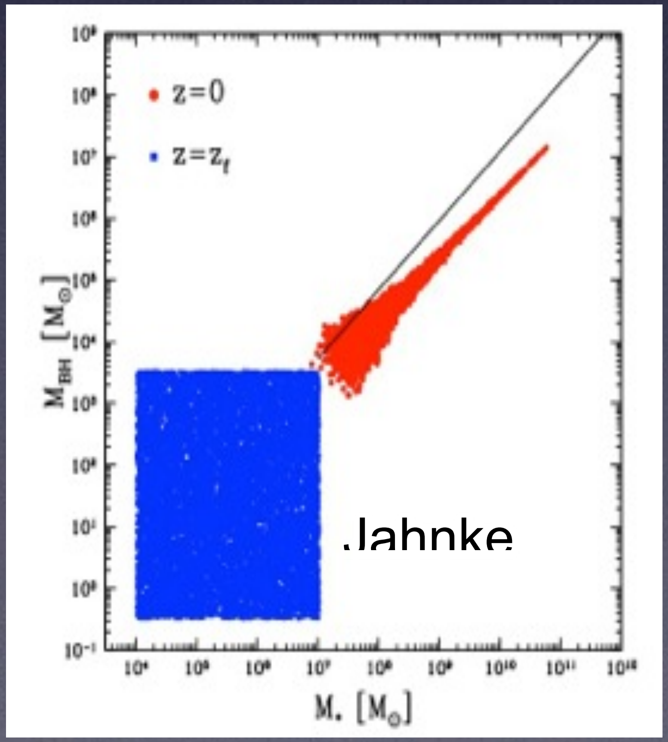
Peng 2007:

- **galaxy merging average out extreme values of MBH /M∗, converging toward a narrow correlation**

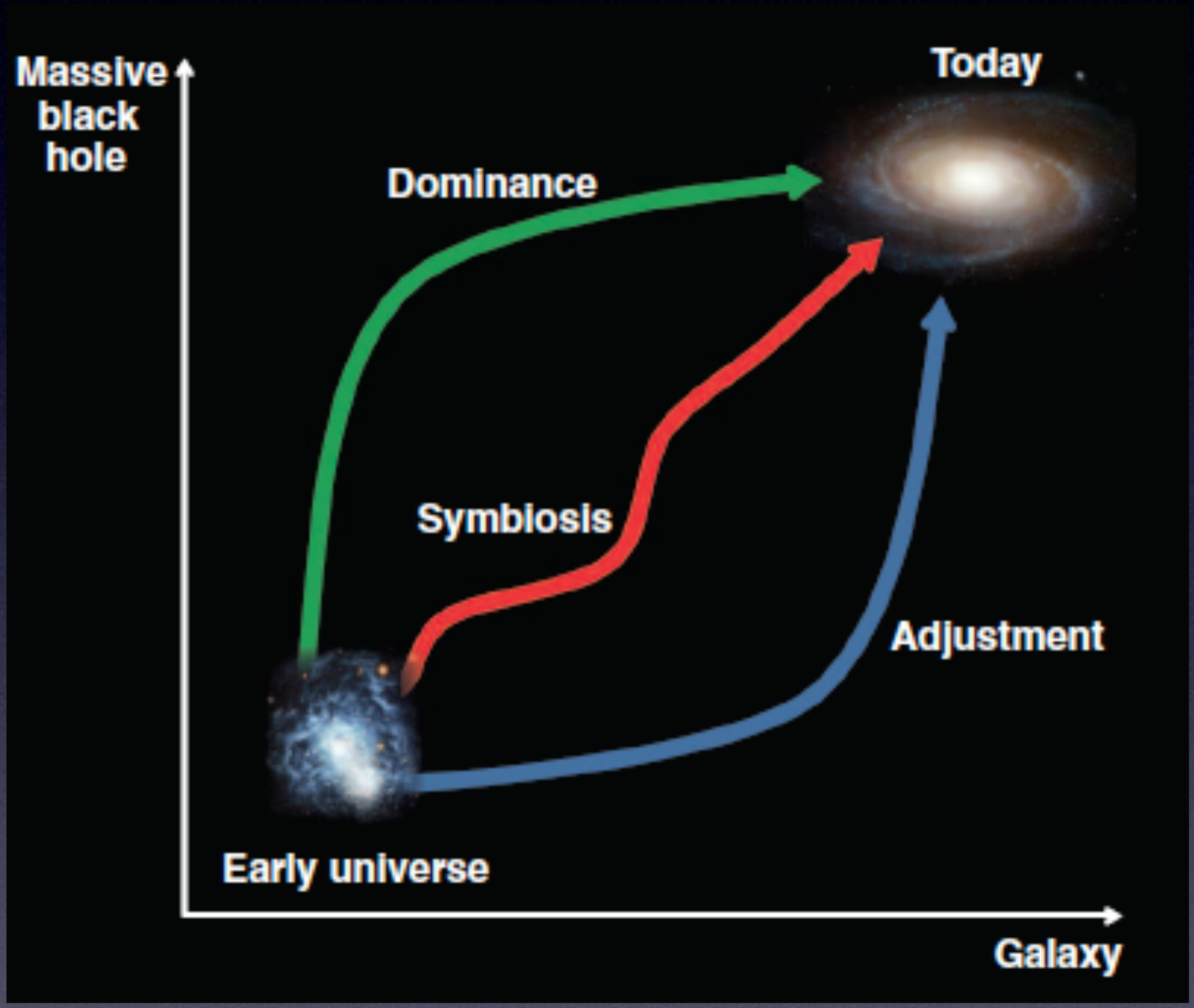
Jahnke & Maccio 2010:

- **number of mergers consistent with that of standard merger trees models for the formation of galaxies (and SMBH)**





Galaxy - Massive Black Hole growth



Volonteri 2012, Science

- Merging
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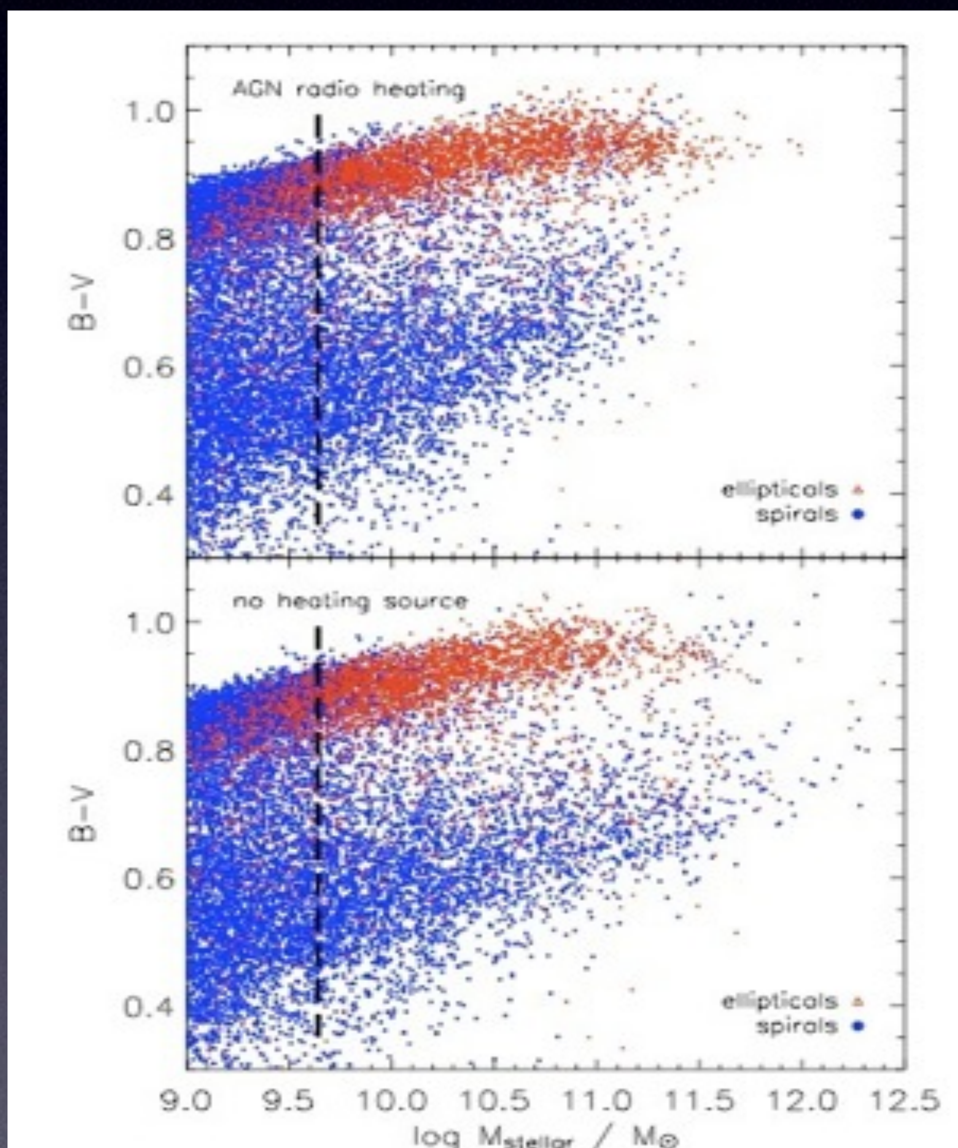
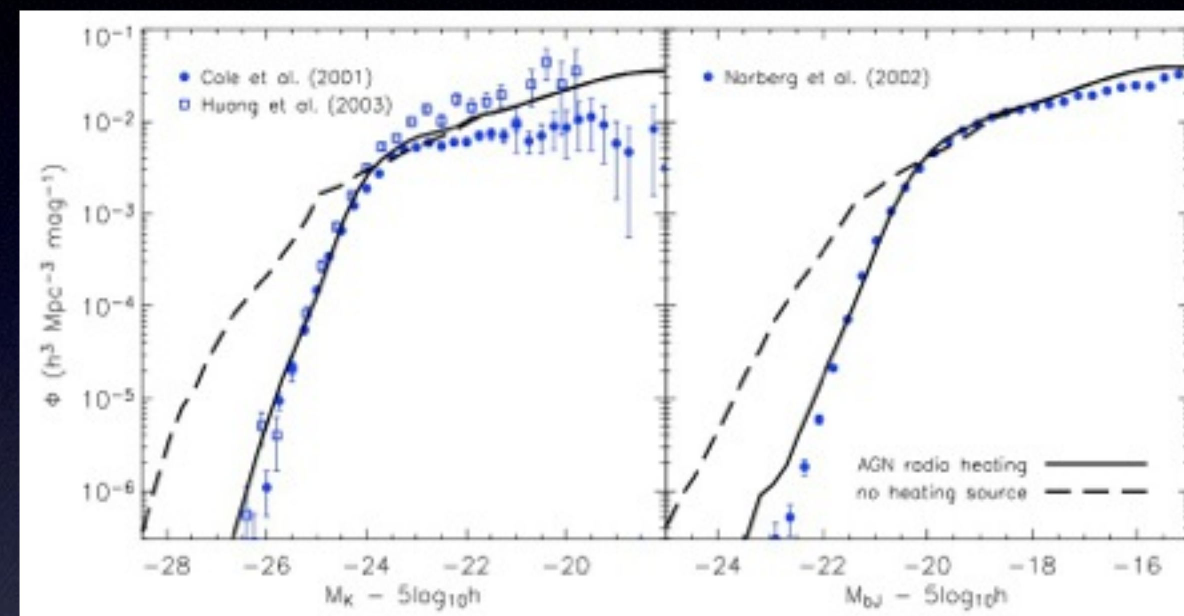
AGN feedback

- AGN heat ISM stopping star formation and accretion





Without AGN heating SAMs:

1. **overpredict luminosities of massive galaxies by ~2 mags**

and/or

2. **predict a number of massive blue galaxies higher than observed**

Menci et al. 2006, Croton+2006, Millenium

AGN feedback could be the solution. Observations of feedback in action can confirm.

AGN Feedback & AGN accretion mode

Quasar mode

- Major mergers
- Minor mergers
- Galaxy encounters
- Activity periods are strong, short and recurrent

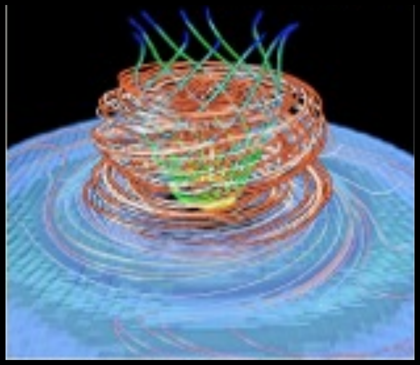
- AGN density decrease at z<2 is due to:
  - decrease with time of galaxy merging rate
  - Decrease with time of encounters rate
  - Decrease with time of galactic cold gas left available for accretion
- Feedback is driven by AGN radiation

Menci+ 2003,2004,2006,2008

Zubovas & King 2012, 2014

- Radio mode
- Low accretion-rate systems tend to be radiatively inefficient and jet-dominated
- Low level activity can be ~continuous
- Feedback from low luminosity AGN dominated by kinetic energy

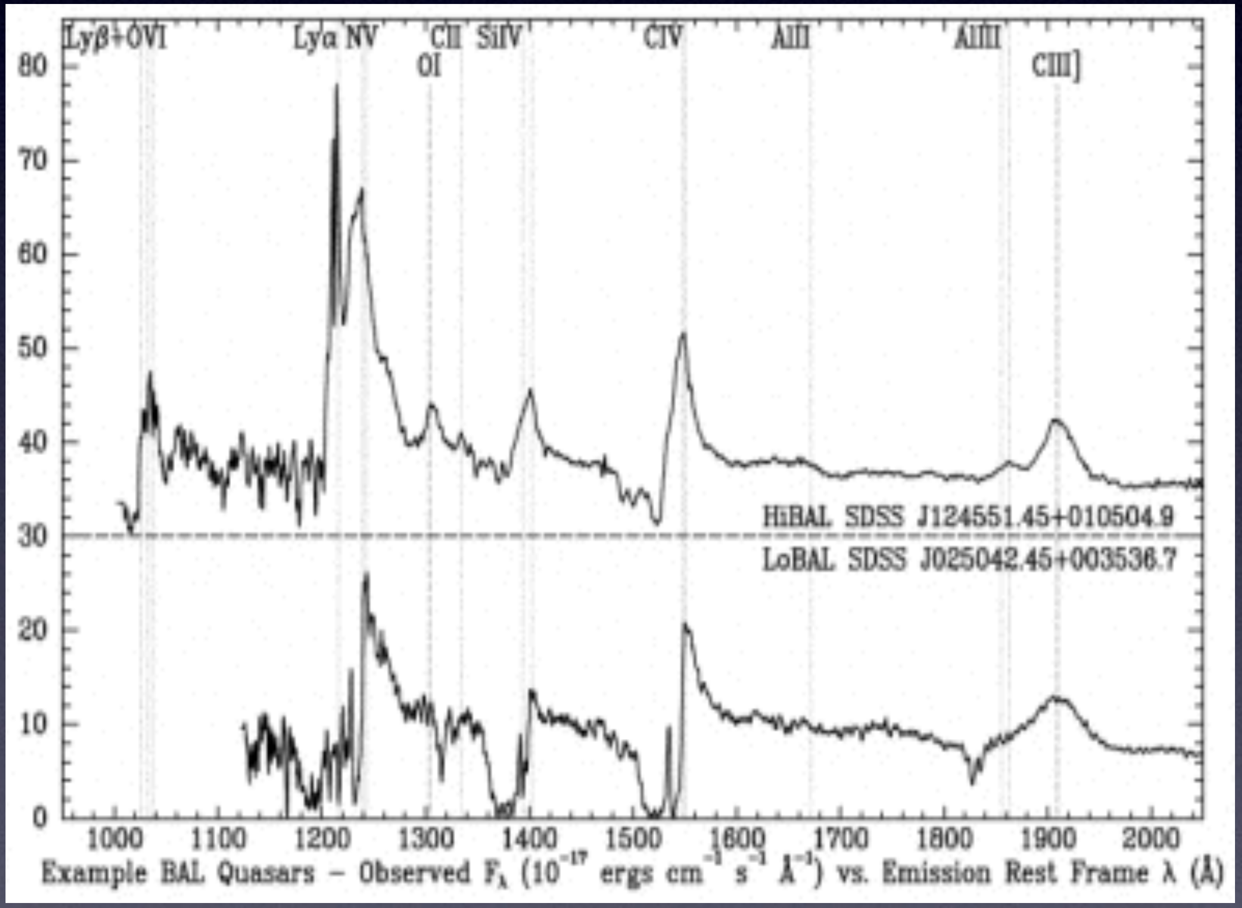
Croton+ 2006



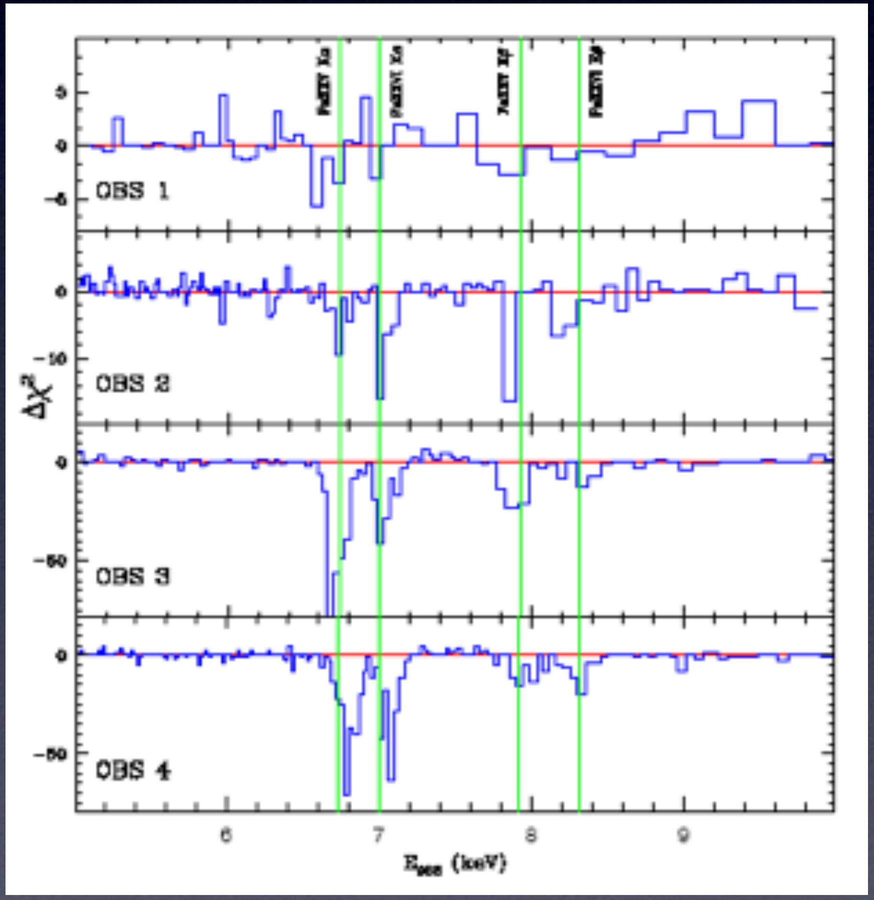
AGN winds and outflows

Fast winds with velocity up to a fraction of c observed in the central regions of AGN.
Likely originate from the acceleration of disk outflows by the AGN radiation field
Crenshaw+03, Pounds+03, Reeves+09, Moe+09

BAL QSOs (10-40% of all QSOs)



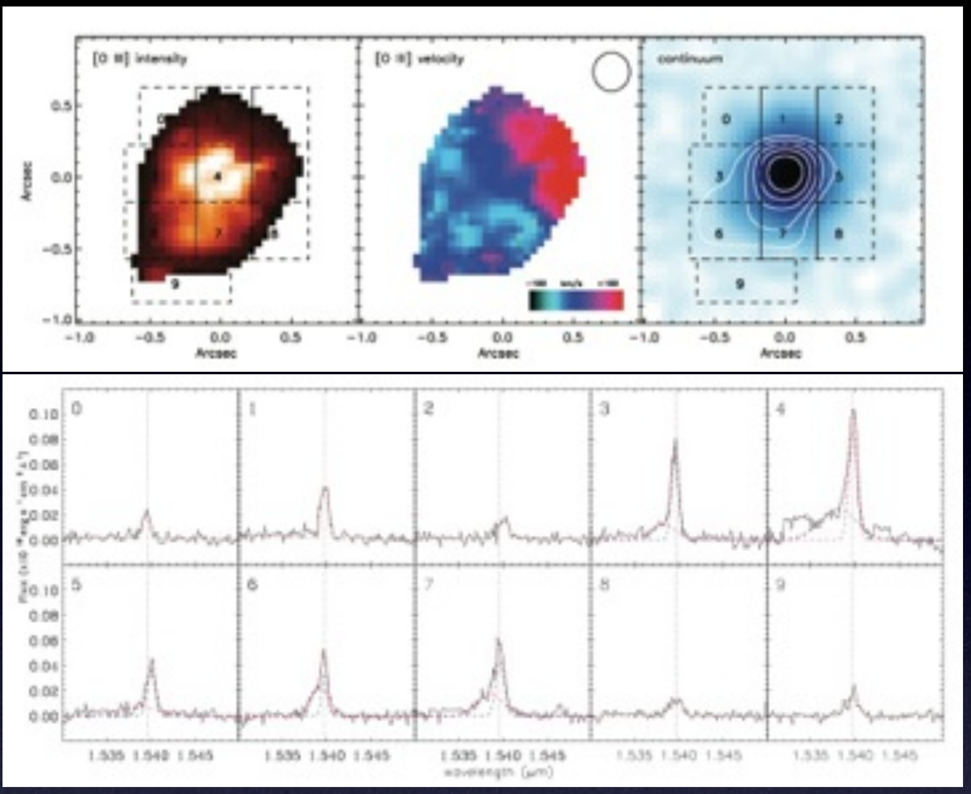
NGC1365 Risaliti+ 2005

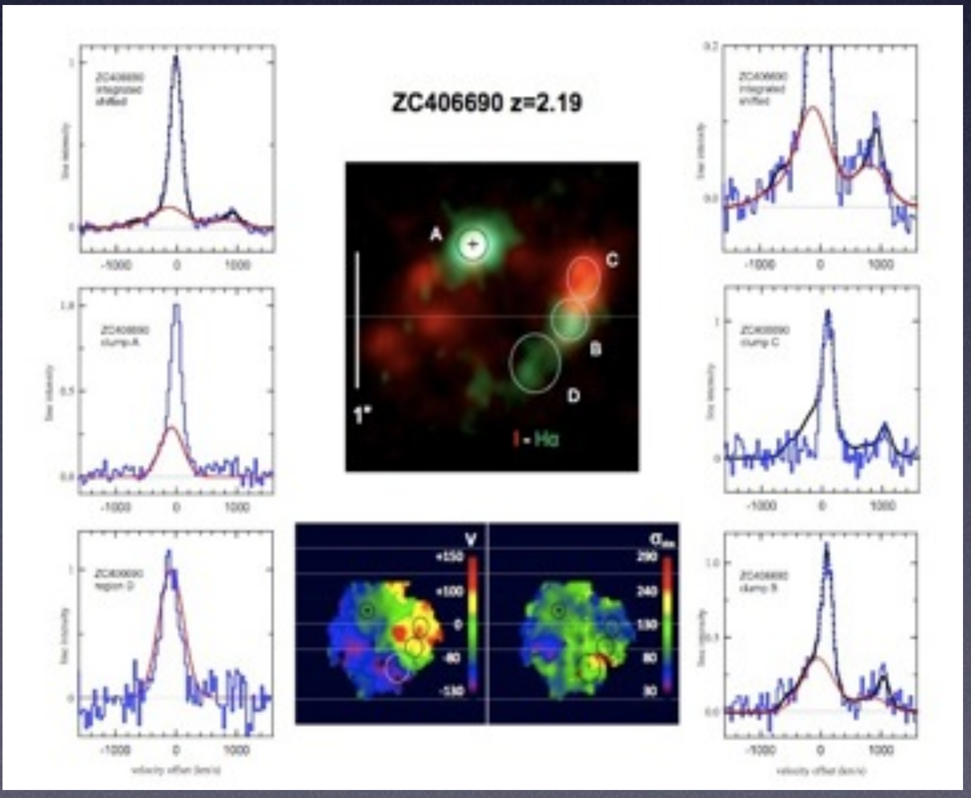


- Atomic gas makes small fraction of the gas present in a galaxy disk
- Physical scale unknown or small (nuclear)

Galaxy wide outflows of atomic gas

- IFU observations of [OIII] emission of radio galaxies, up to z=2.5 (Nesvabda+ 2006, Swinbank+ 2005,2006)
  - Extent of broad [OIII] similar to radio emission
  - Ekin~1-40% Ejet
- SMMJ1237, a QSO in a z~2 ULIRG (Alexander+ 2010)
  - Extent of broad [OIII] ~4-8kpc
  - E_{kin}~10^{59} ergs over 30 Myr ~ binding energy of galaxy spheroid
- Giant SF clumps at z~2 (Genzel+2011)
  - Broad Hα, mass outflow rate > SFR





Galaxy wide molecular outflows

MRK 231

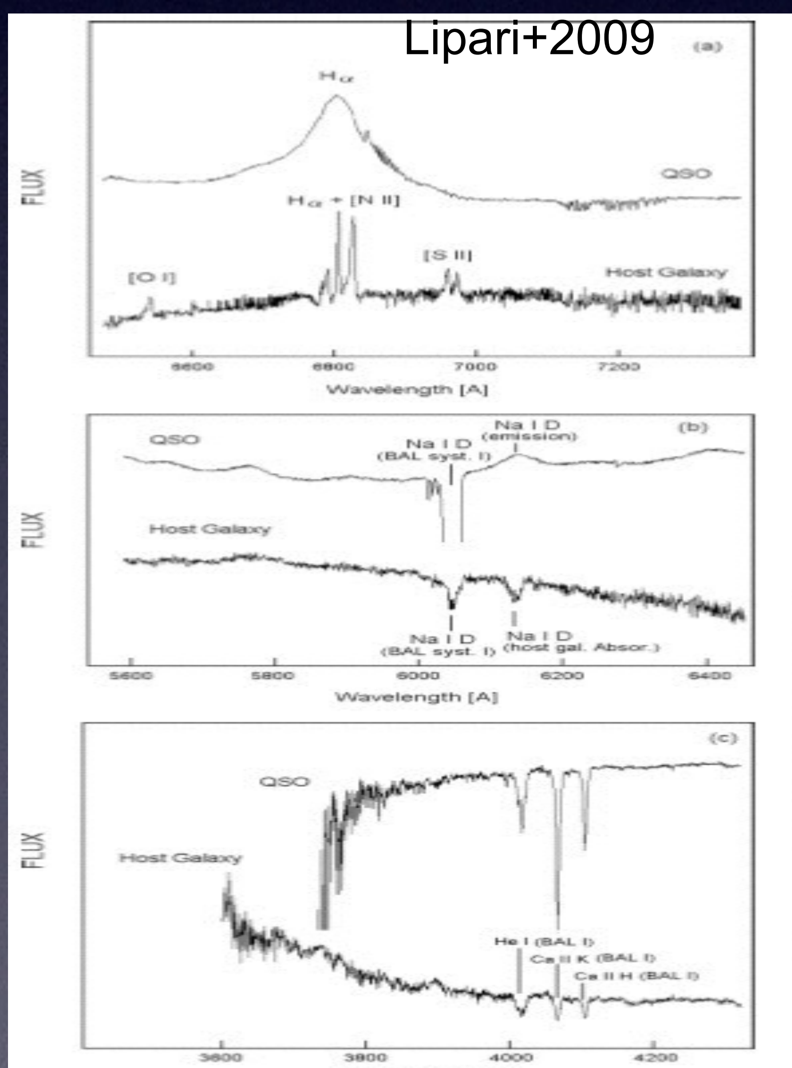
The nearest ULIRG with SFR= 200 $M_{\odot}$/yr

late stage merger system

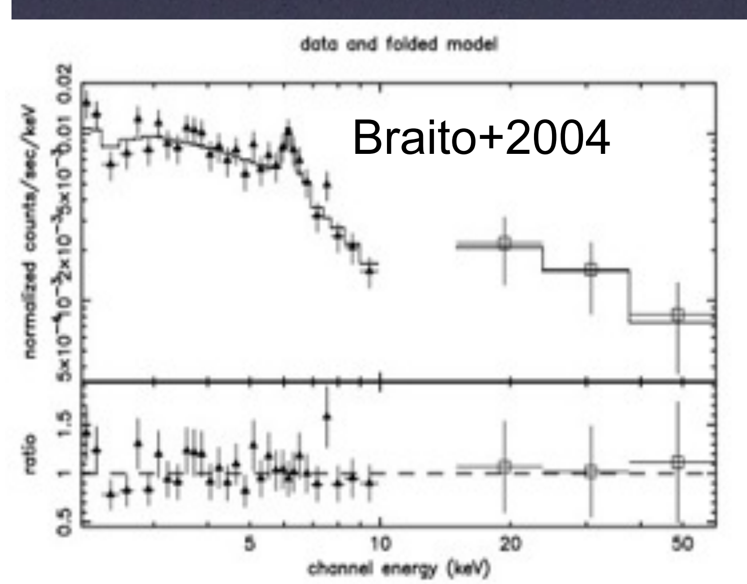
hosting a obscured, luminous (BAL) QSO

high luminosity (L_{bol}~10^{46} erg/s),

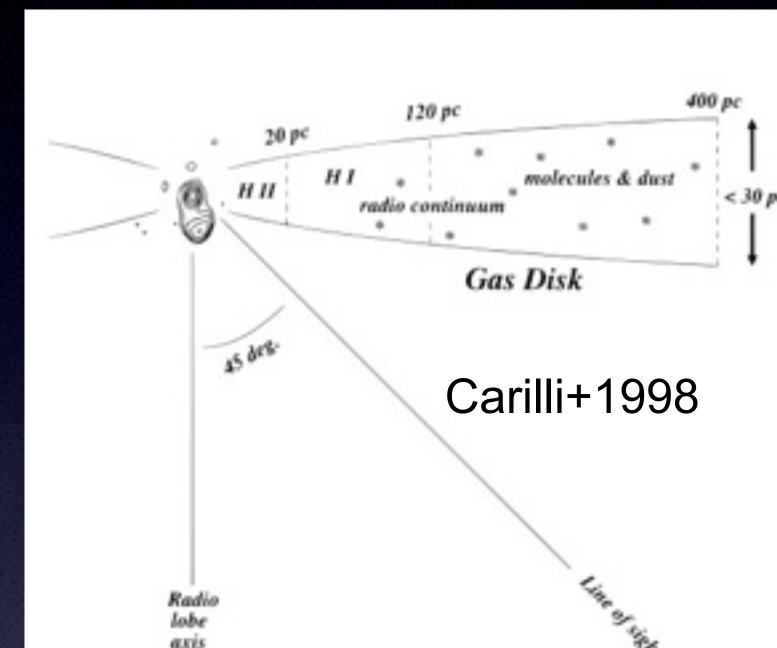
highly obscured (N_H~10^{24} cm^{-2})



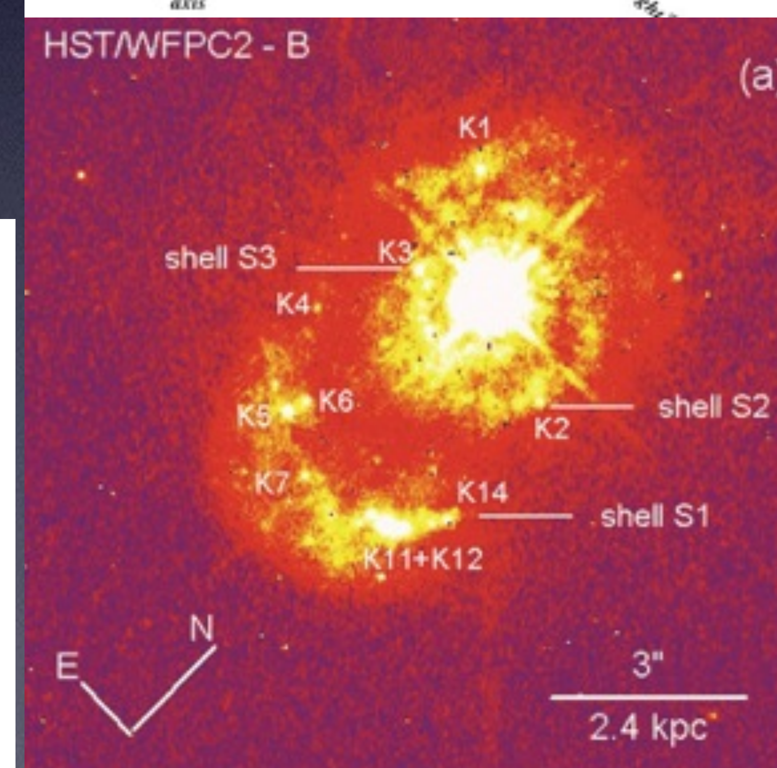
Lipari+2009



Braito+2004



Carilli+1998



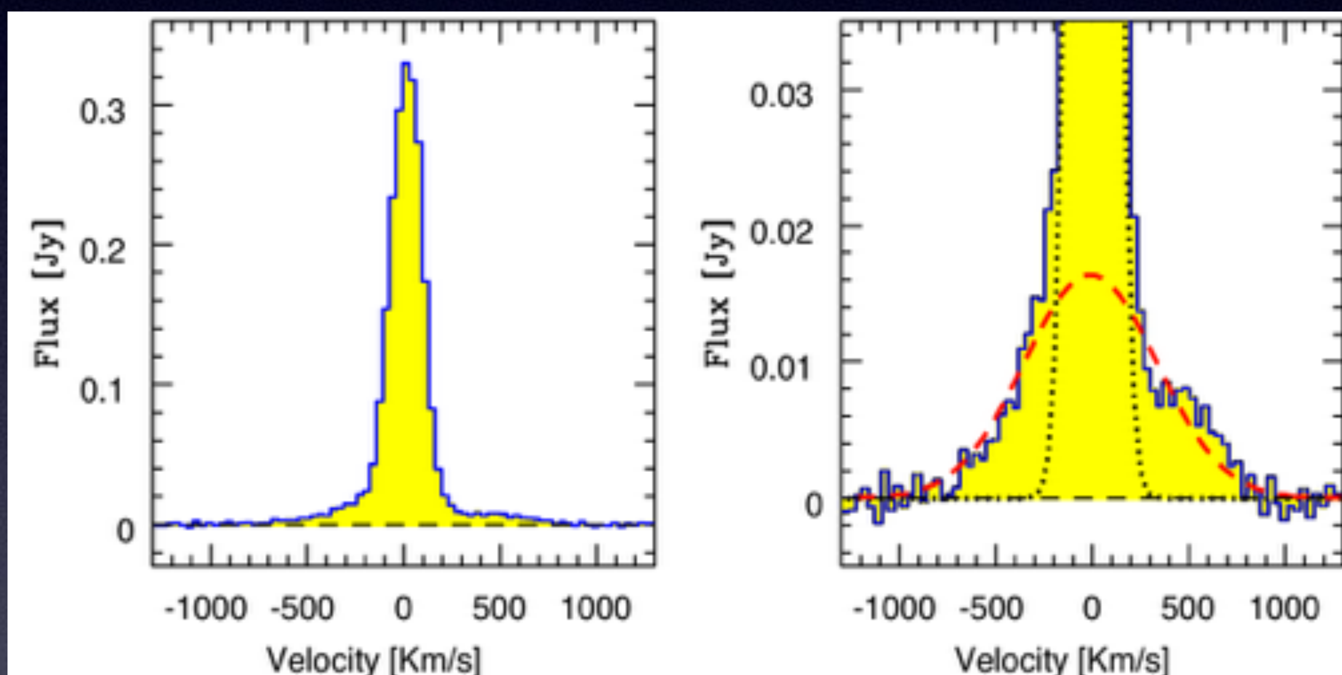
Galaxy wide molecular outflows : Mrk 231

Narrow component of CO(1-0) + low surface brightness broad component extending out to +-800 km/s
FWZI = 1500 km/s

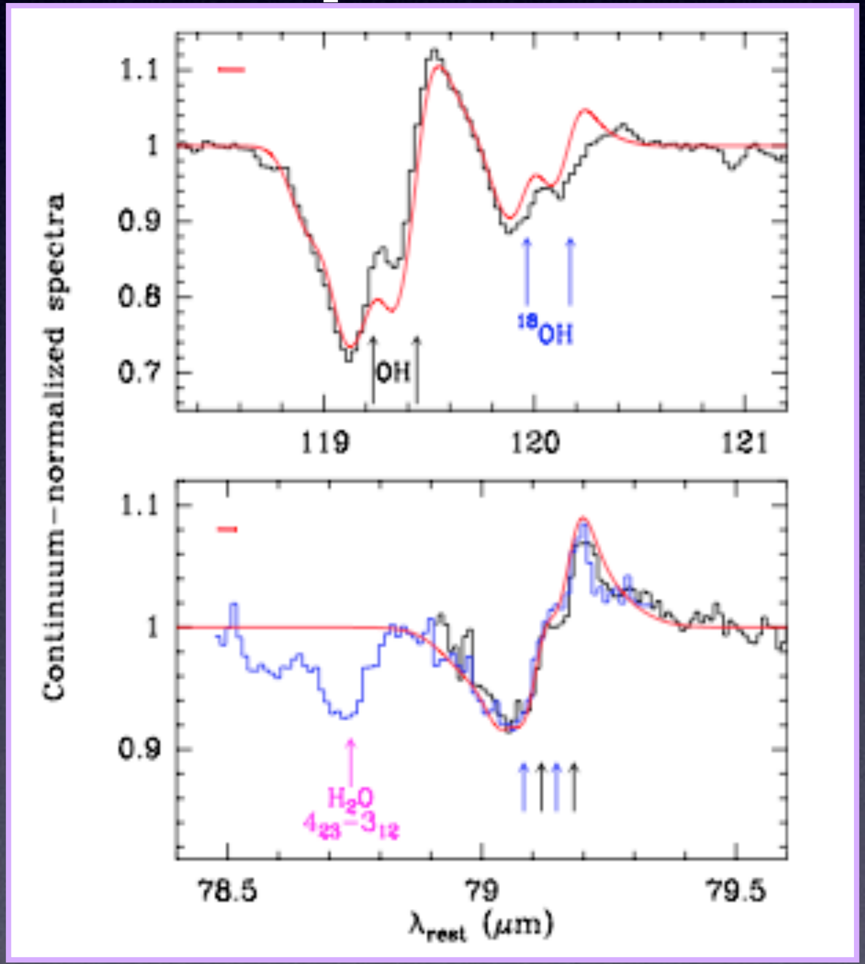
P-cygni profile in OH line
Herschel/PACS (Fischer et al. 2010)

Spatial resolution

Feruglio et al. 2010



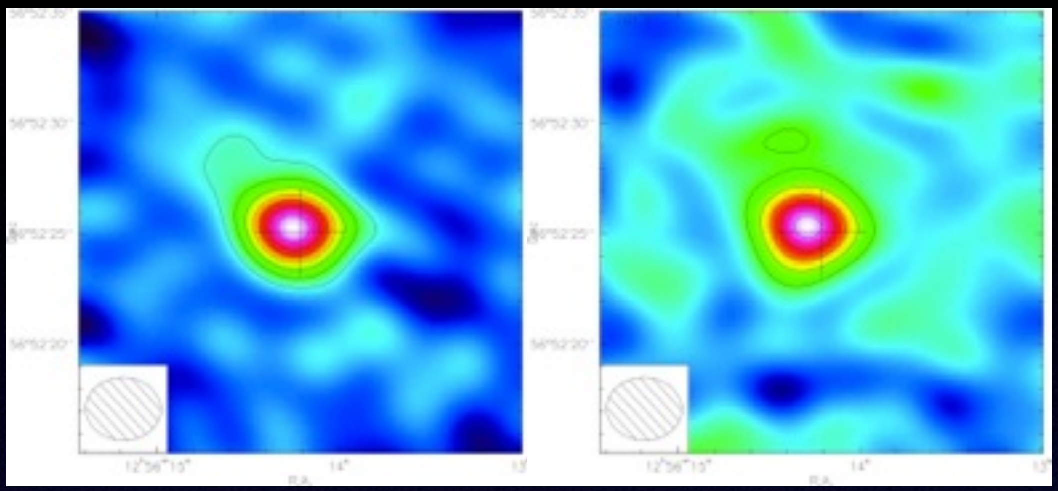
Absorption line

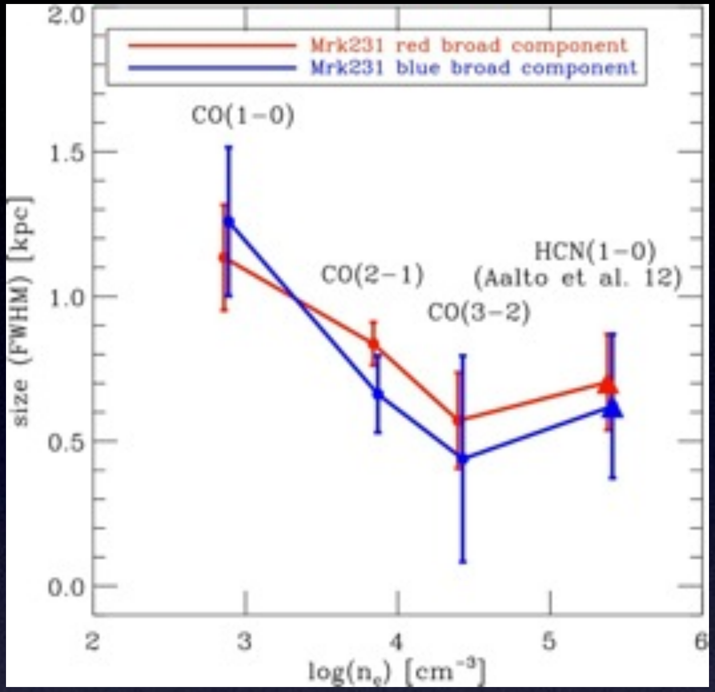


Mass in the OF: $M(H_2) > 7\ 10^7\ M_\odot$

Uncertainties due to unknown conversion factor CO-to-H2

Galaxy wide molecular outflows : Mrk 231





Size measured ~ 1 kpc

Mass loss rate; $dM(H_2)/dt \sim 1000\ M_\odot/yr$

MASS LOSS RATE LARGER THAN THE SFR : GAS DEPLETION TIME OF THE ORDER 10^7-10^8 YR

NO STELLAR POPULATIONS YOUNGER THAN 10^6 YEARS IN THE CENTRAL KPC (LIPARI ET AL.)

Kinetic energy of outflowing gas: **$E = 1.2\ 10^{44}$ erg/s = a few % L_{Bol} ($5\ 10^{45}$ erg/s) of the AGN**

compatible with models of AGN-driven outflow through a shock wave.

Emission of CO at +- 800 km/s. Mach number is large
If CO is shocked, excitation conditions in the outflow should be different: outflowing gas more excited than low velocity gas.

Galaxy wide outflows : Mrk 231

This extended outflow detected in IFU IR observations of neutral gas as well (Rupke et al. 2011)

NaI

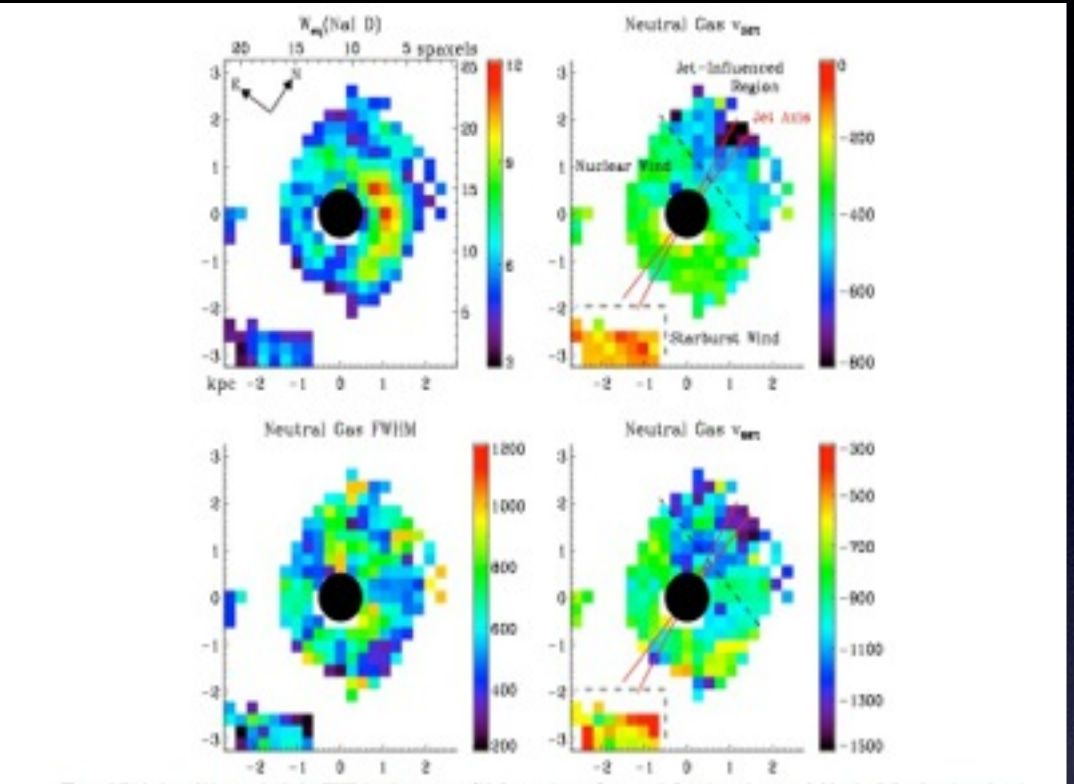
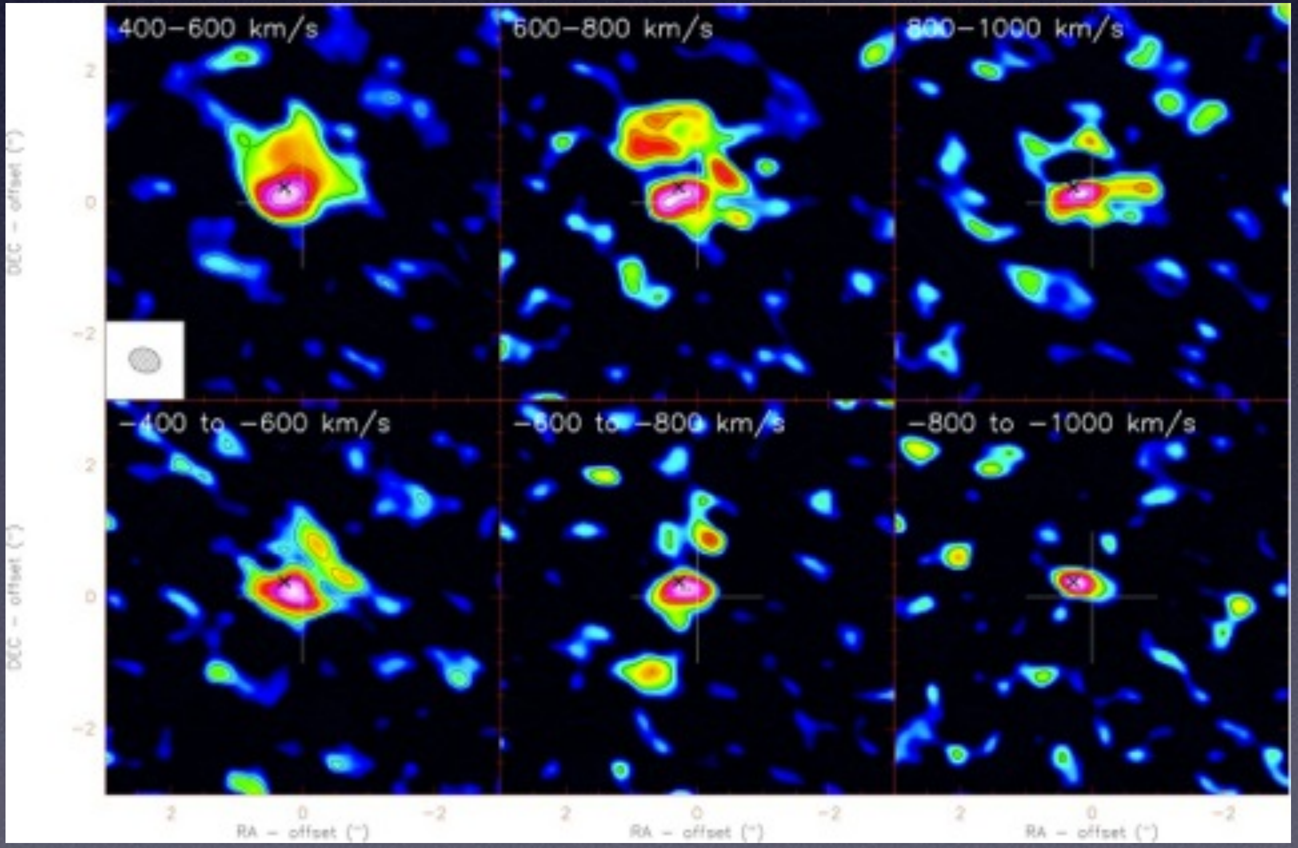


Figure 4. Equivalent width, central velocity, FWHM, and v_{max} maps of Na I D. A nuclear outflow extends from the nucleus up to 2–3 kpc in all directions (as projected in the plane of the sky). The high velocities suggest that the AGN powers the nuclear wind. The northern quadrant of the nuclear wind is further accelerated by the radio jet. A lower-velocity starburst-driven outflow is present in the south.

Neutral gas absorption traces 2-3 Kpc scale outflow with v ~ 1100 km/s powered by the AGN

Also a blueshifted HI region, probably outflow powered by star formation.

CO(2-1)



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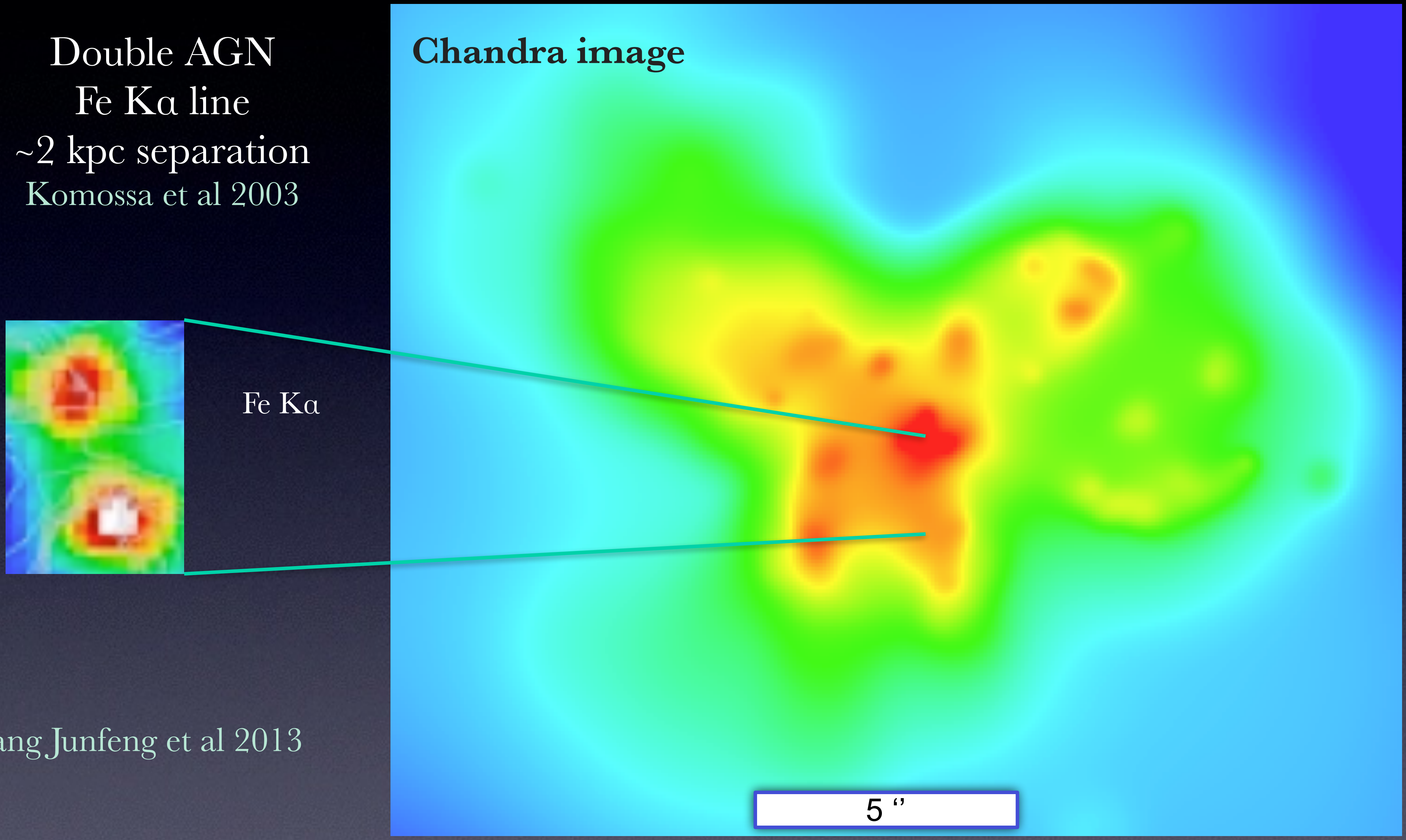
Merging massive BHs : NGC6240

Double AGN
Fe Kα line
~2 kpc separation
Komossa et al 2003



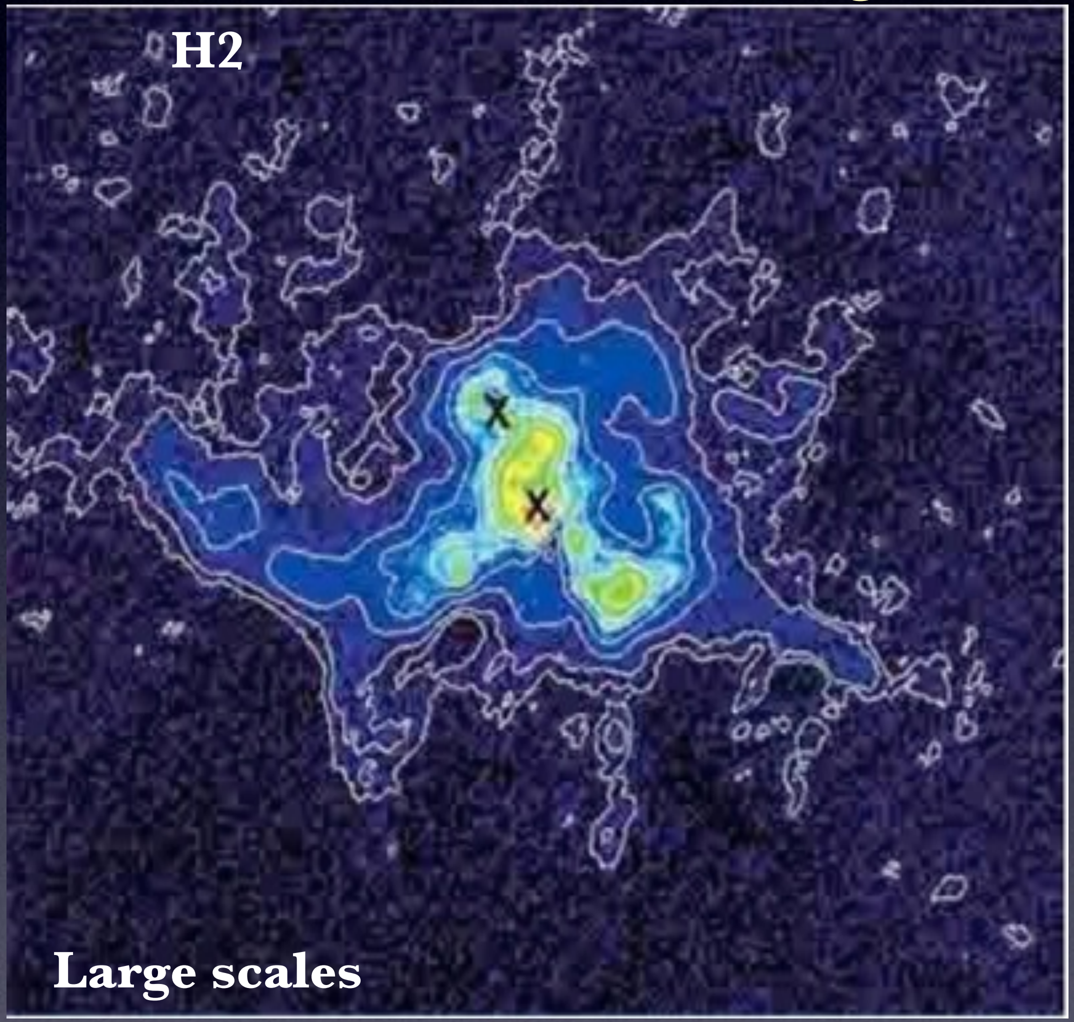
Wang Junfeng et al 2013

NGC6240: a complex system CO outflow

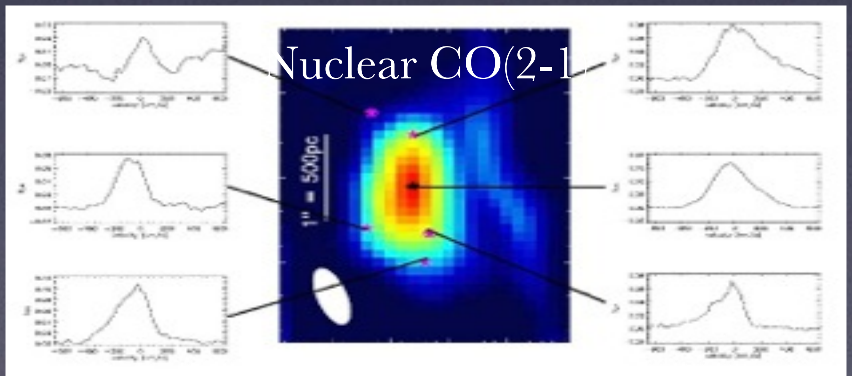
Major merger in early stage of 2 gas rich spirals, with complex morphology, streamers, tidal tails
2 AGN nuclei both heavily obscured, with L(2-10) keV > 10^{44} erg/s and M(BH) > 10^{8} M$_\odot$

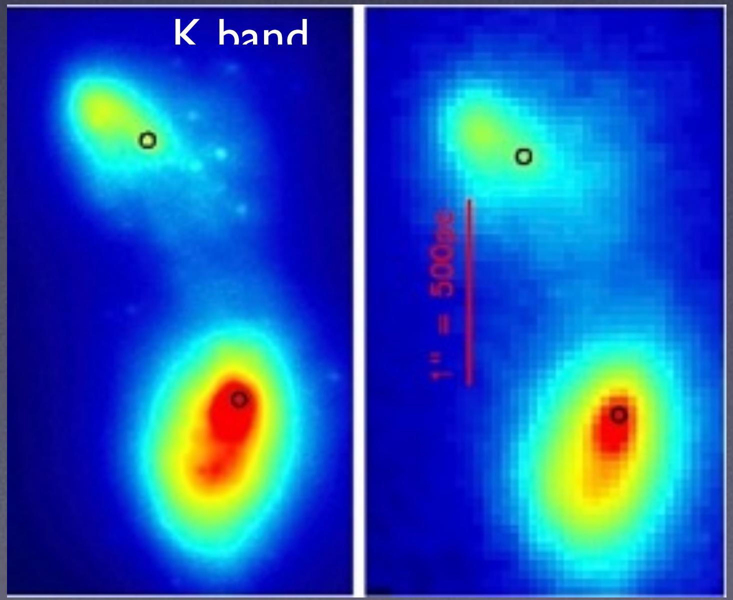
Hα **nebula with bipolar pattern (east-west) : wind sock heating the ISM**

H2 emission, tracer of shocked gas



Max et al. 2005



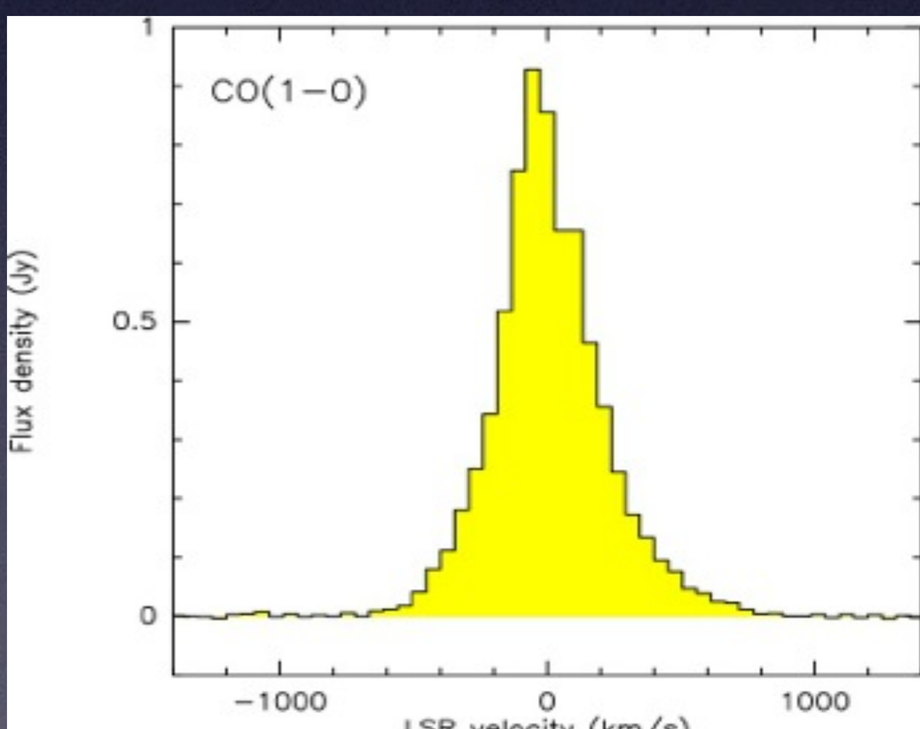


NGC 6240: a complex system with a CO outflow

New sensitive PdBI observations of CO(1-0) : broad CO(1-0) detected out to +- 800 km/s

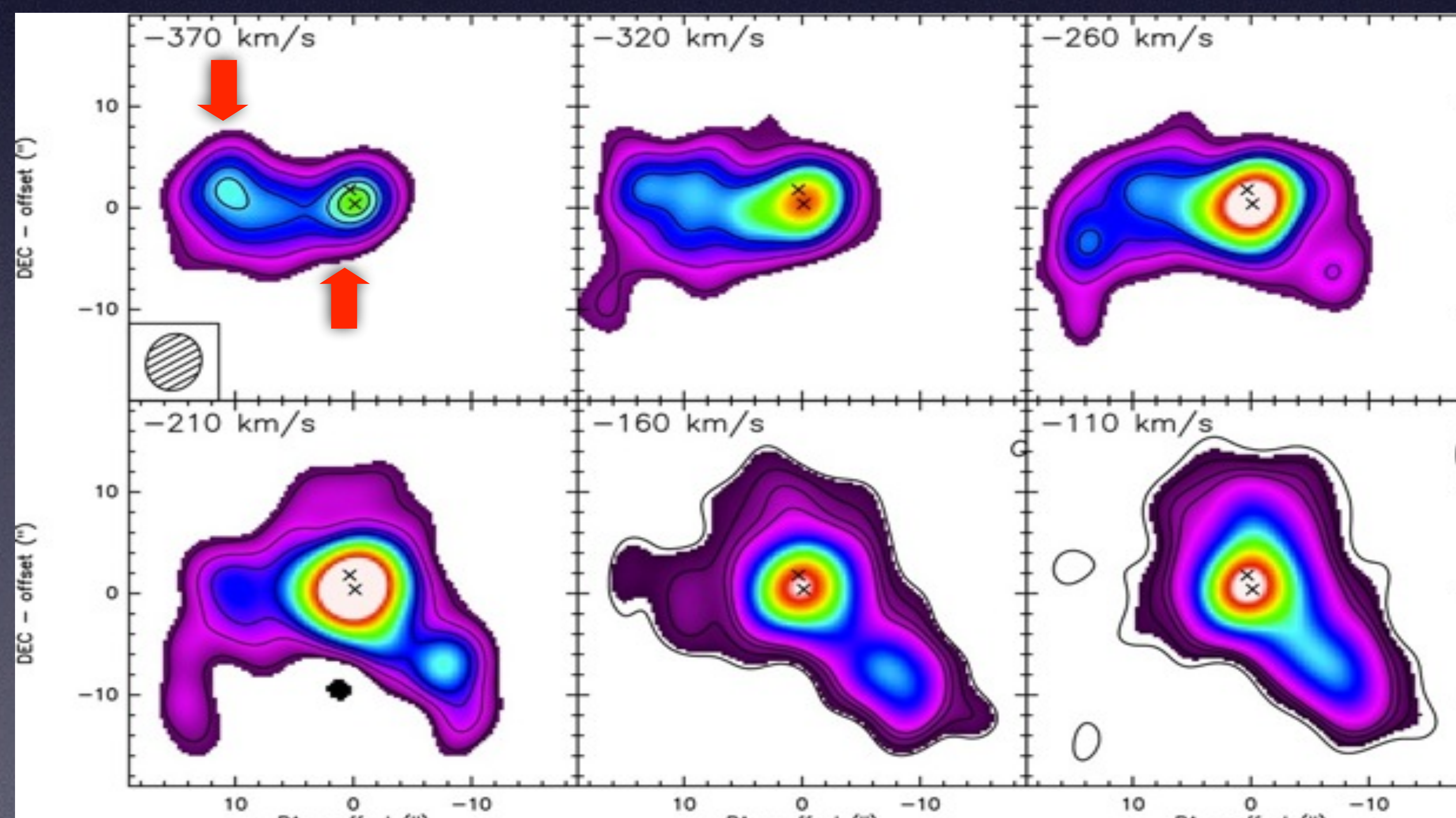
Central concentration of CO in between the 2 AGN : M(H2) ~ 5 10^9 Msun

Blue-shifted extended structures detected on scales of 7 kpc
Mass of the central concentration M(H2) ~ 5 x 10^9 Msun
Outflow M(H2) ~ 7 x 10^8 Msun



CO(1-0) channel maps

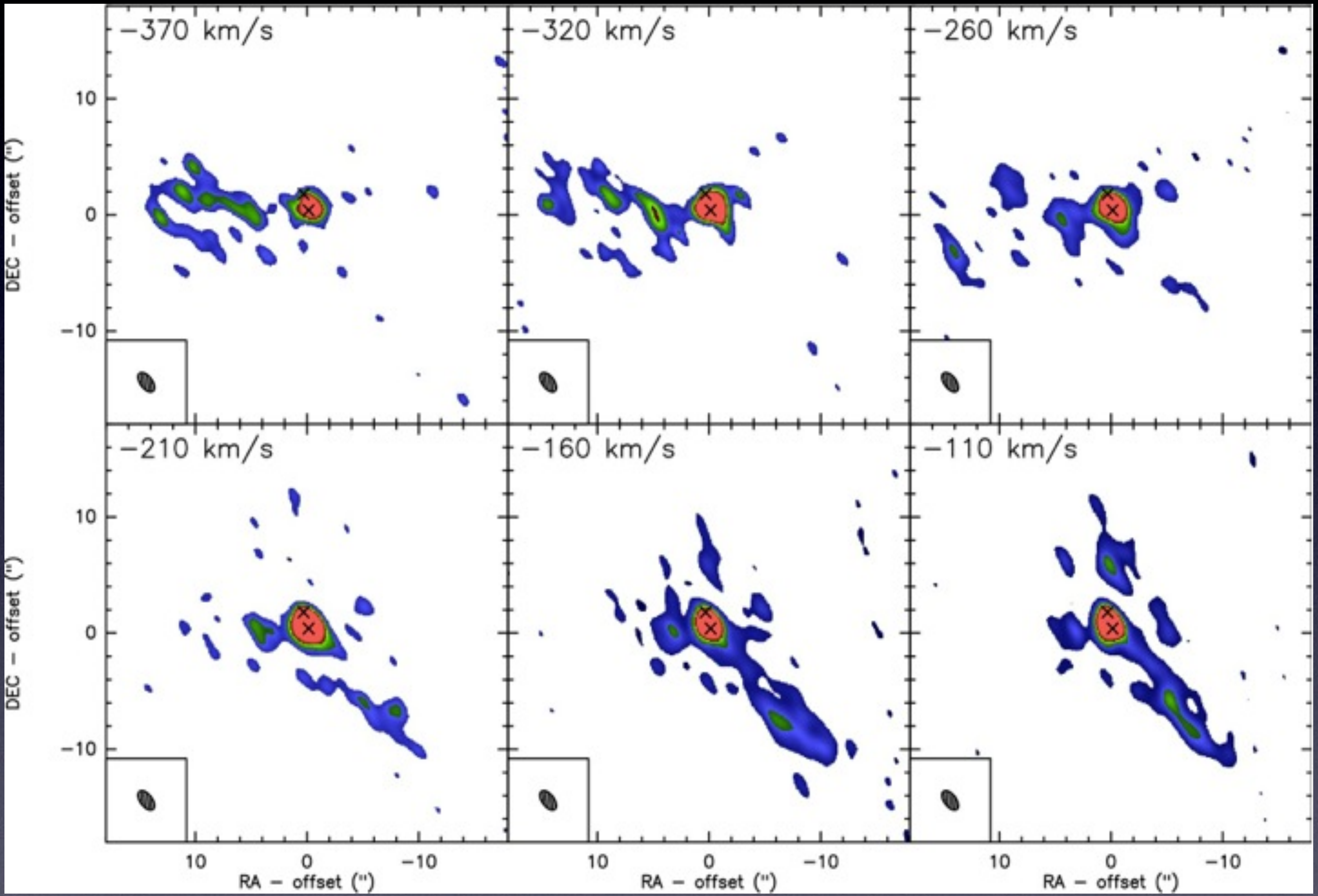
Feruglio et al. 2013



NGC 6240: a complex system with a CO outflow

CO(1-0) map in velocity channels, high spatial resolution

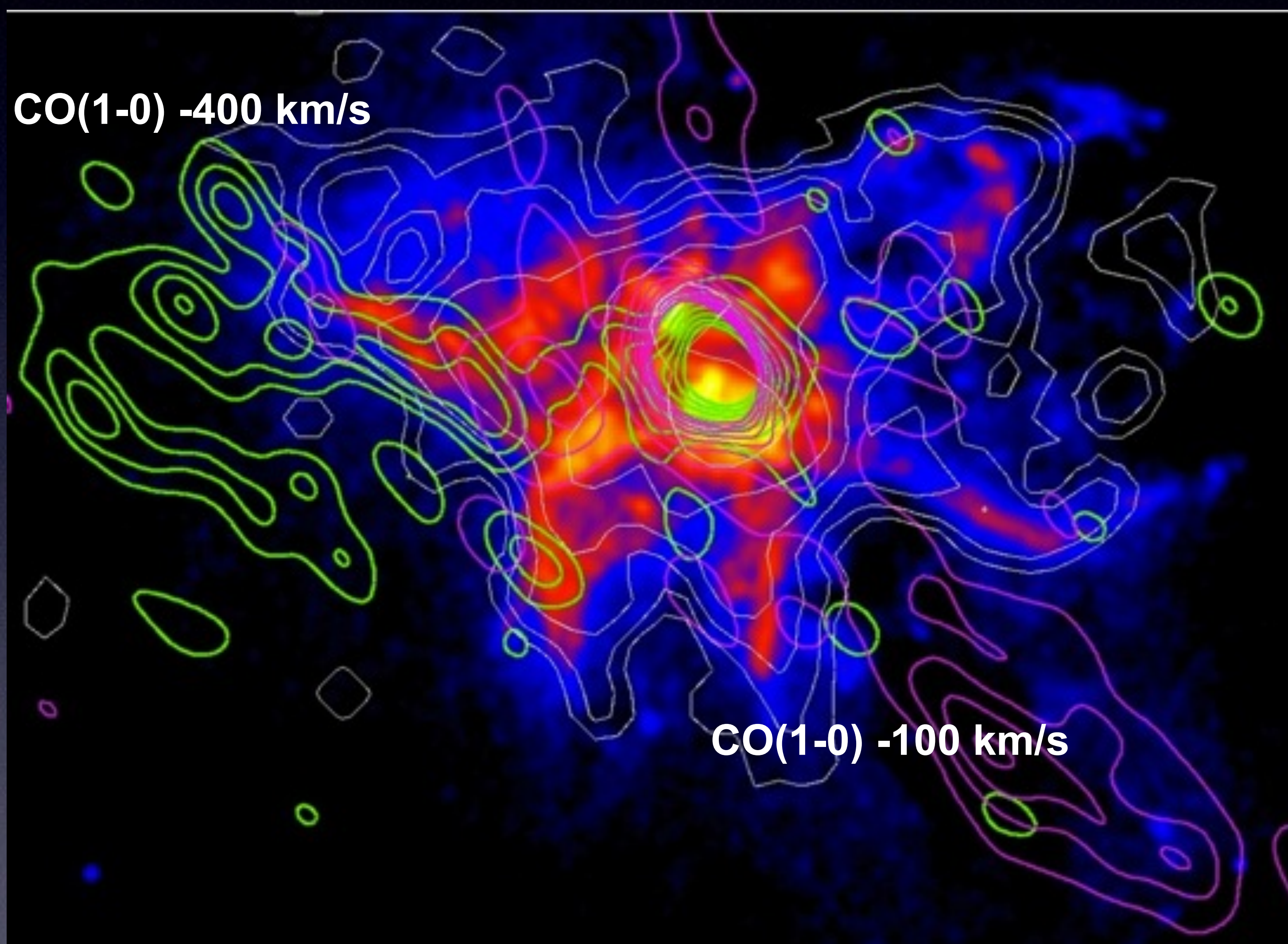
Feruglio et al. 2013

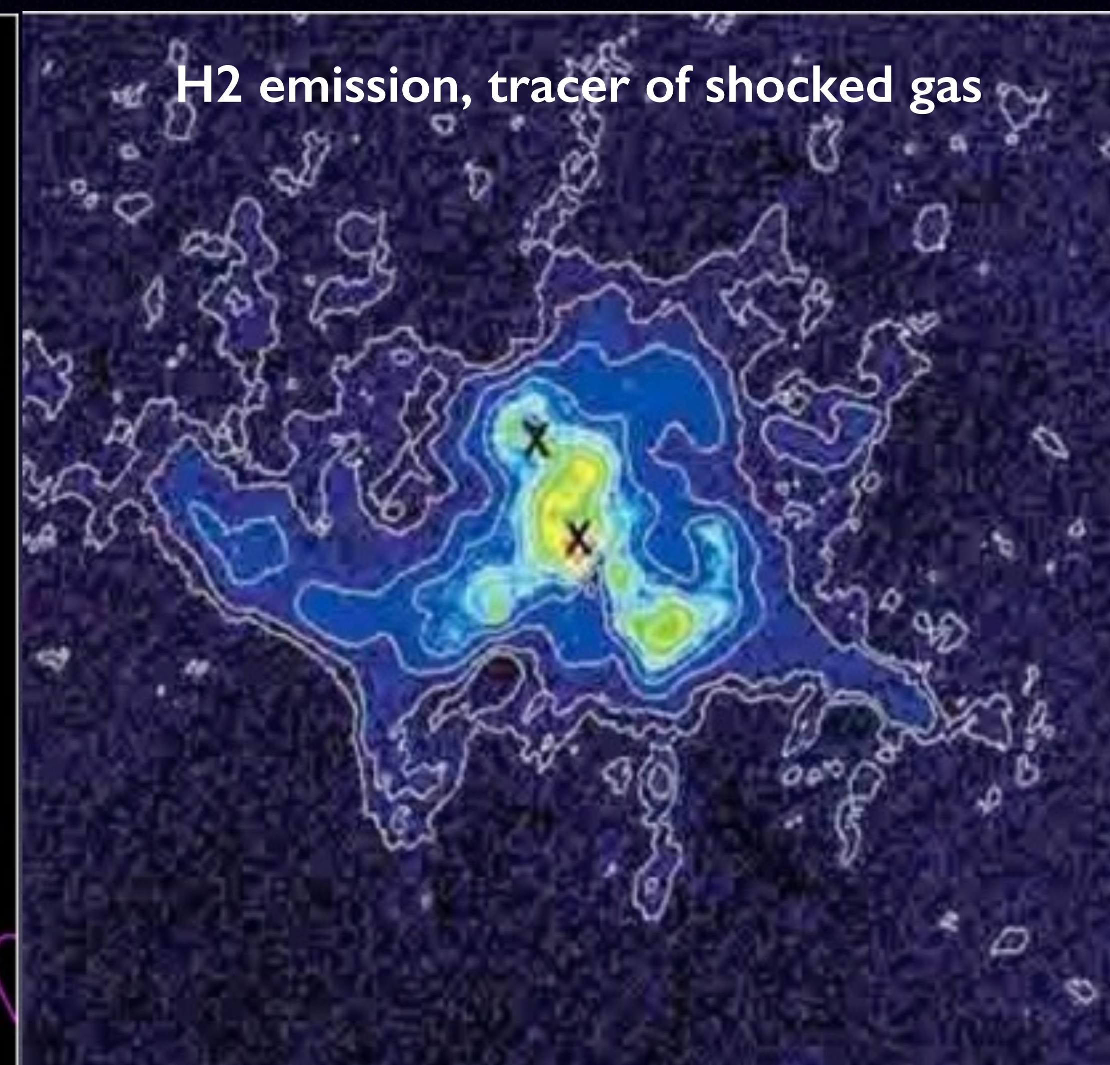


NGC 6240: a complex system with a CO outflow

Hα nebula traces biconical pattern aligned E-W: super-wind from the southern AGN shock-heats the ISM

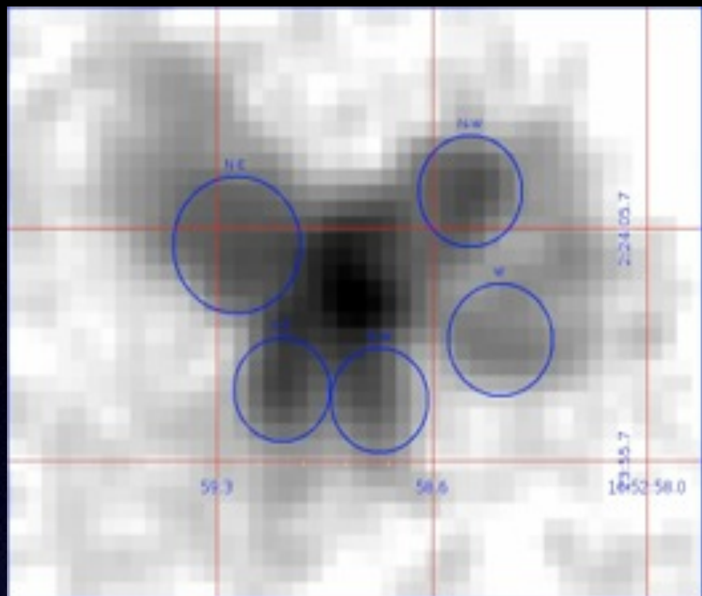
CO at -100 kms/ coincides with the dust lane seen in HST image in the S-W region
CO with -400 km/s coincident with Hα filaments in the Eastern region





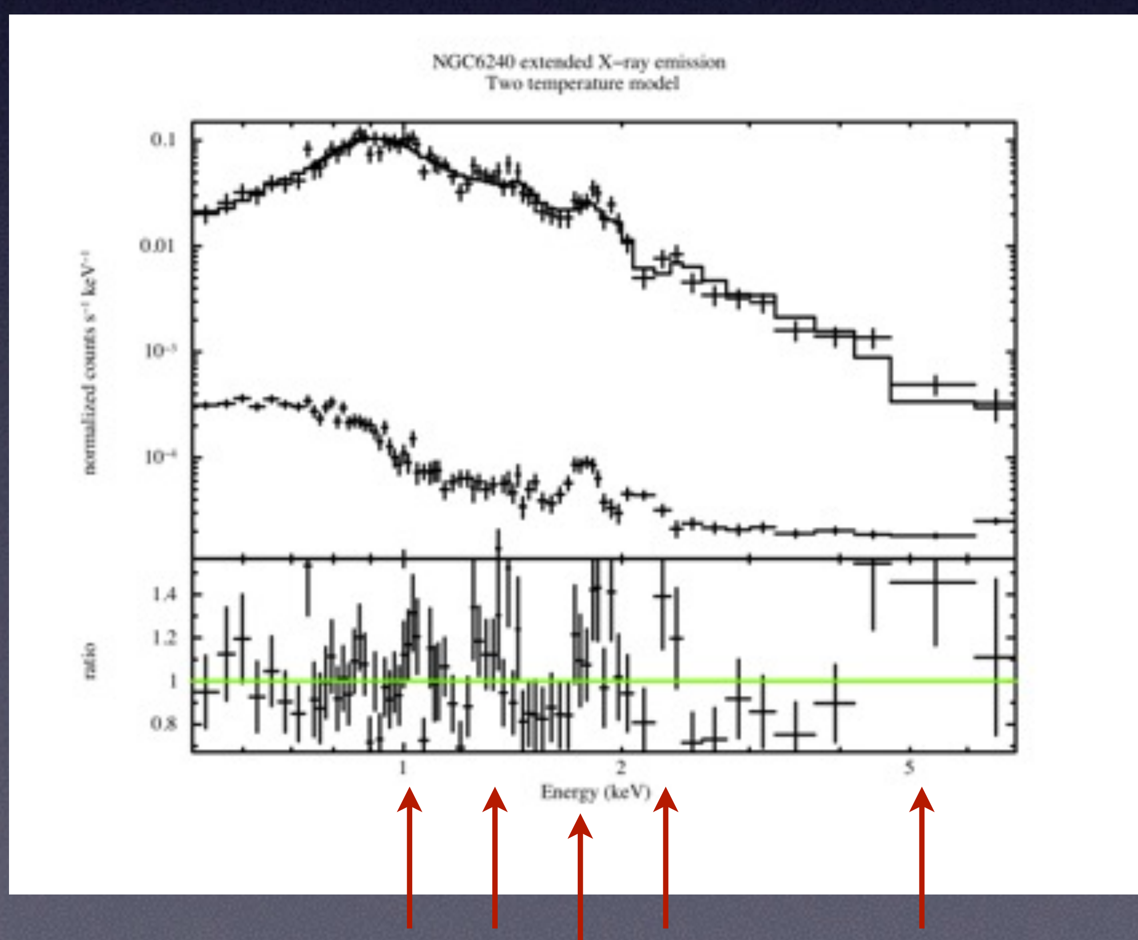
If CO outflow from the southern AGN,   mass loss rate of several 100 $M_\odot$ /yr

*S*patially resolved spectroscopy with *Chandra*

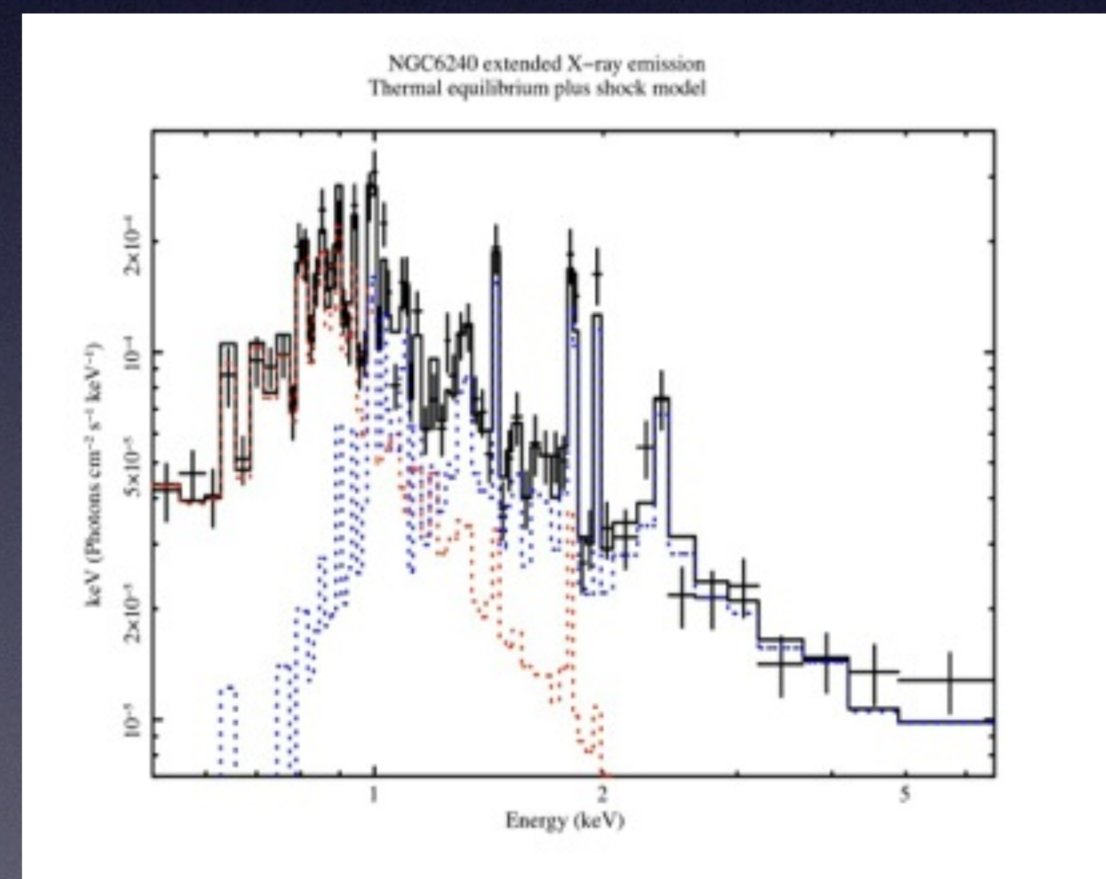


Analysis of the Chandra X-ray:
evidence for shocked gas at the position of the Hα emission, suggests that a shock is propagating eastwards and compressing the molecular gas, while crossing it.

Thermal equilibrium, 2 Temperatures

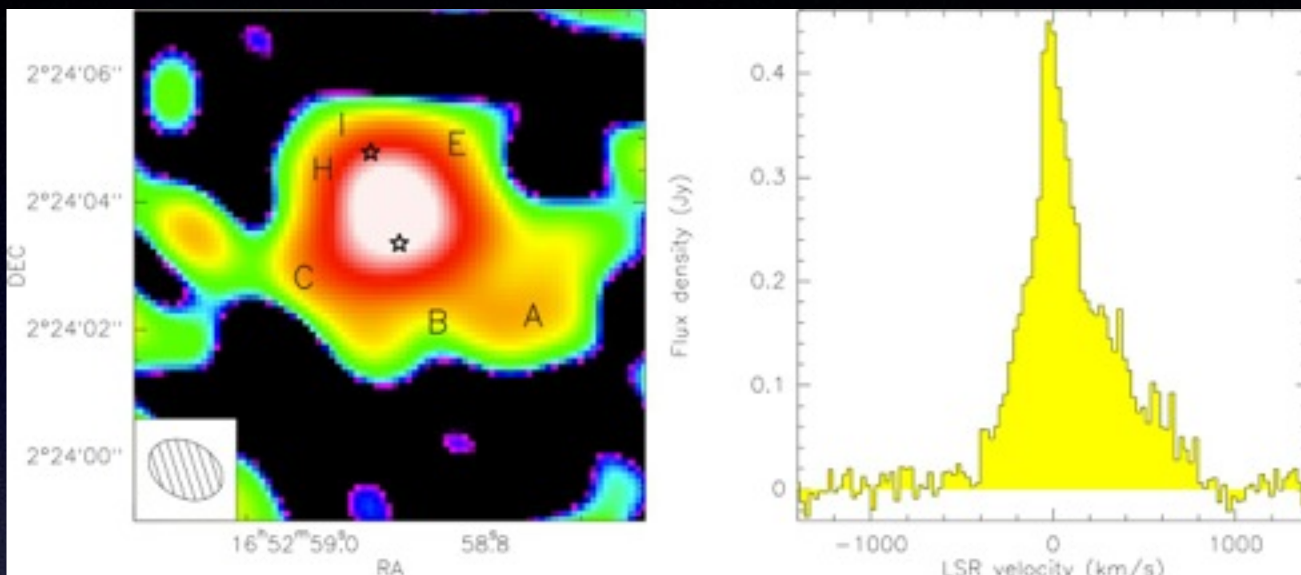


Thermal + shock , prominent emission lines



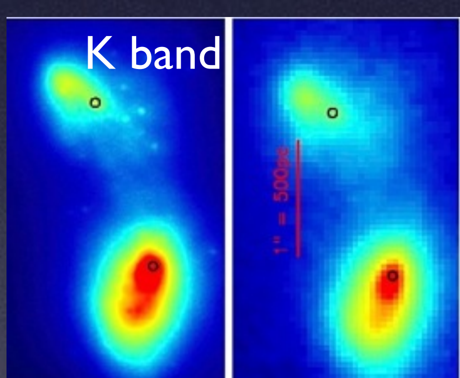
Residuals at pos of Mg, Si, S emission

NGC 6240 nuclear region

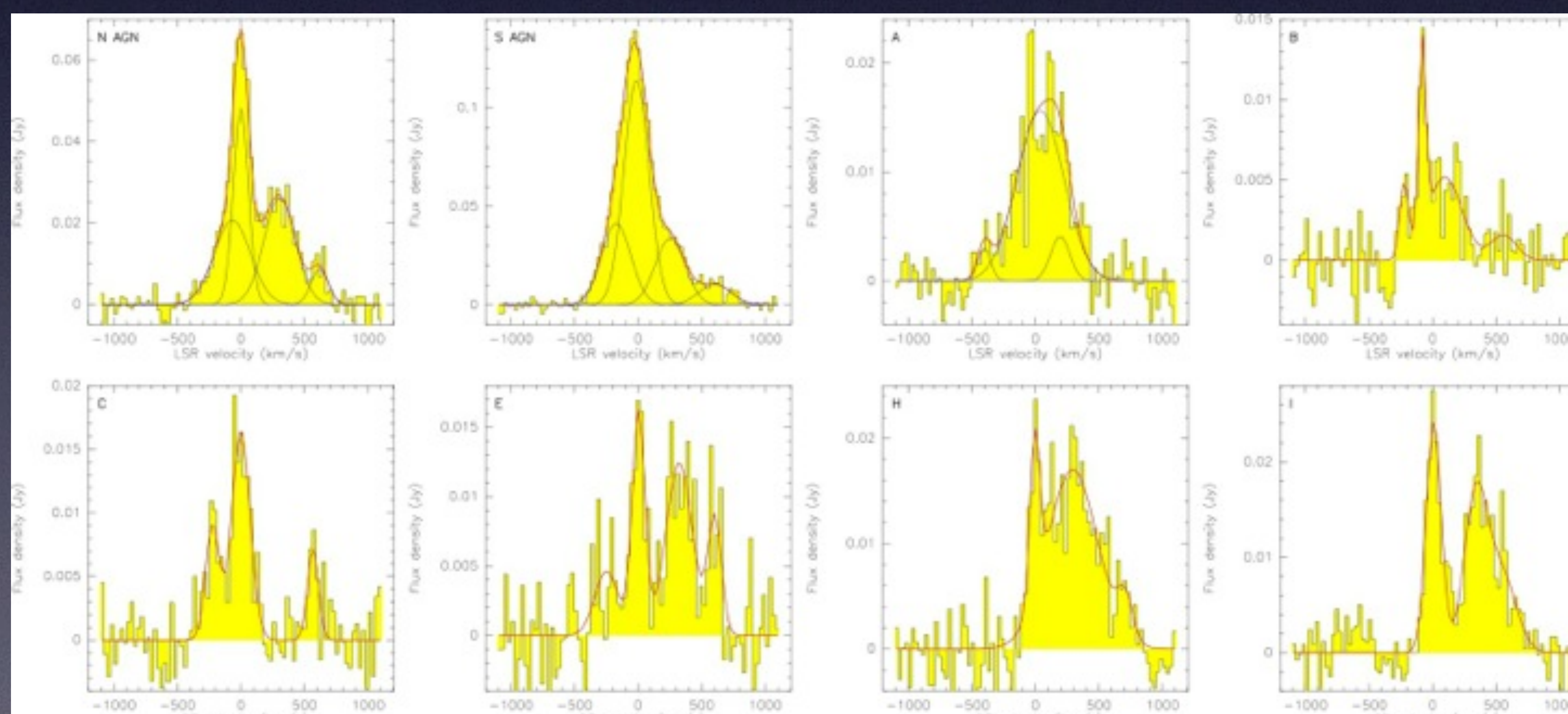


Central concentration of CO in between the 2 AGN
+
Extended diffuse emission (see Tacconi+1999)

Complex velocity field showing several dynamical components



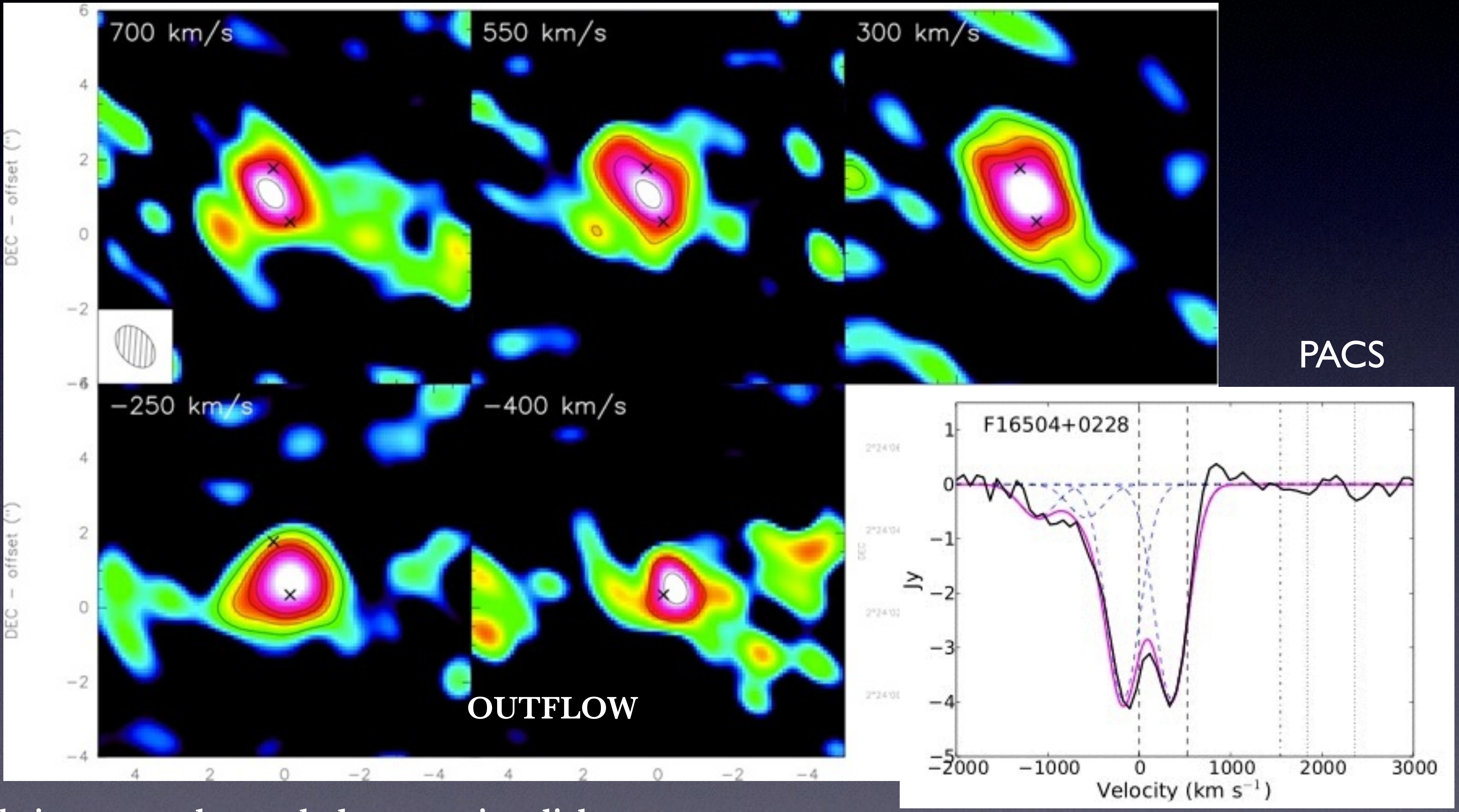
Stars still bound to the progenytors (Engel 2010)



NGC 6240 nuclear region

Red-shifted gas: concentrated between the 2 AGN

Blue-shifted gas centered on the southern AGN



Previously interpreted as turbulent rotating disk
BUT NOW velocity too large for a rotating disk!

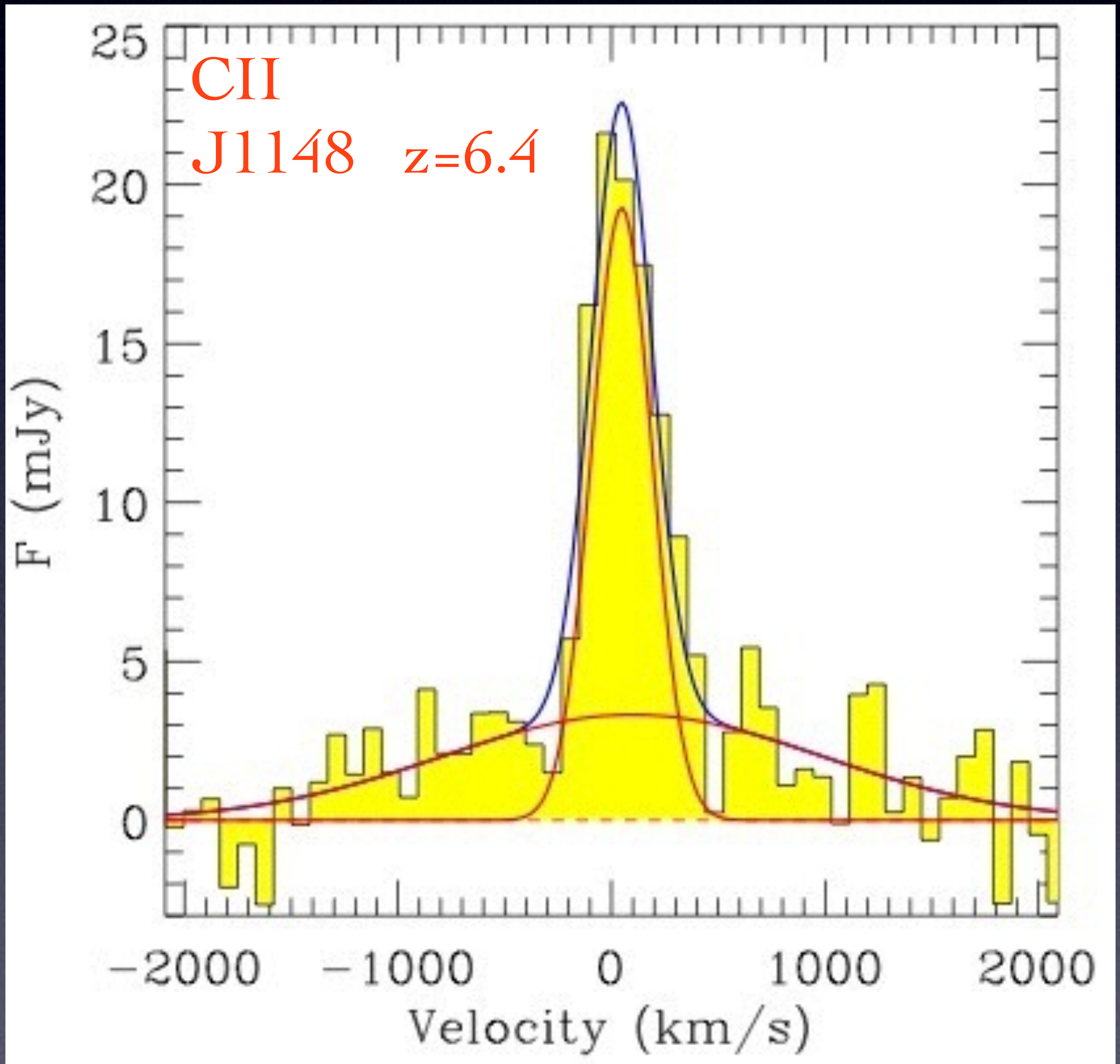
OH absorption: OF with vmax=-1200 km/s
Veilleux+13

Outflows in the distant universe

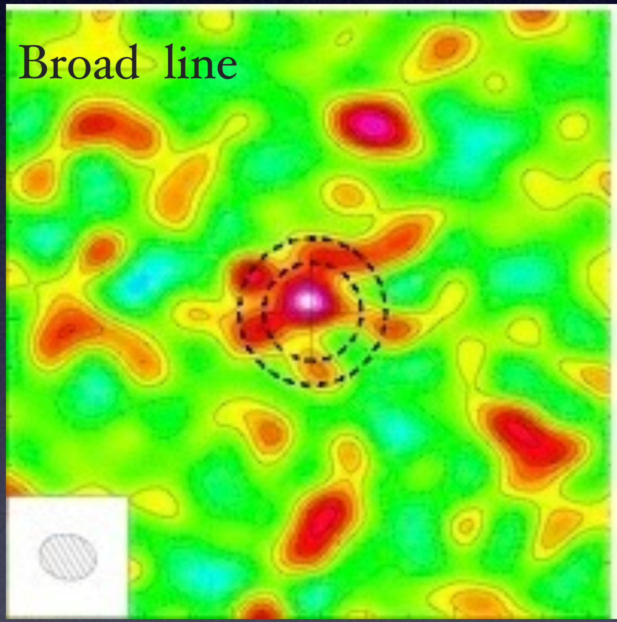
Extremely luminous quasar SDSS J1148 at z=6.4
Host galaxy has SFR ~ 3000 Msun/yr and M(H2) ~ 2 e10 M$_\odot$

Broad wings detected in [CII]158um with FWHM = 2000 km/s (Maiolino et al. 2012)

Vmax = 1300 km/s already points towards AGN-driven outflow and shocks



Mof > 7 e9 Msun <u>under conservative assumptions</u>
(X(C+), n_crit , Temperature)



Broad component concentrated in the center but extended on scales of 16 kpc

gives mass loss rate of dM/dt > 3500 Msun/yr !!!

and kinetic power Pkin > 2 e45 erg/s

< 1% of the AGN LBol

Well above the power injected by SNa = η * SFR * 7e41 (η ~ 0.1)

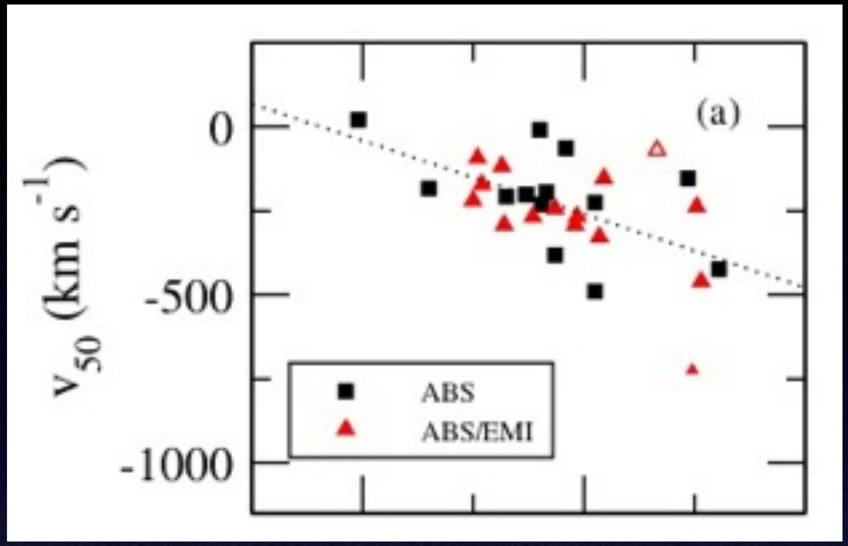
<u>Spatial resolution also at high z to constrain geometry</u>

Summary of AGN extended outflows

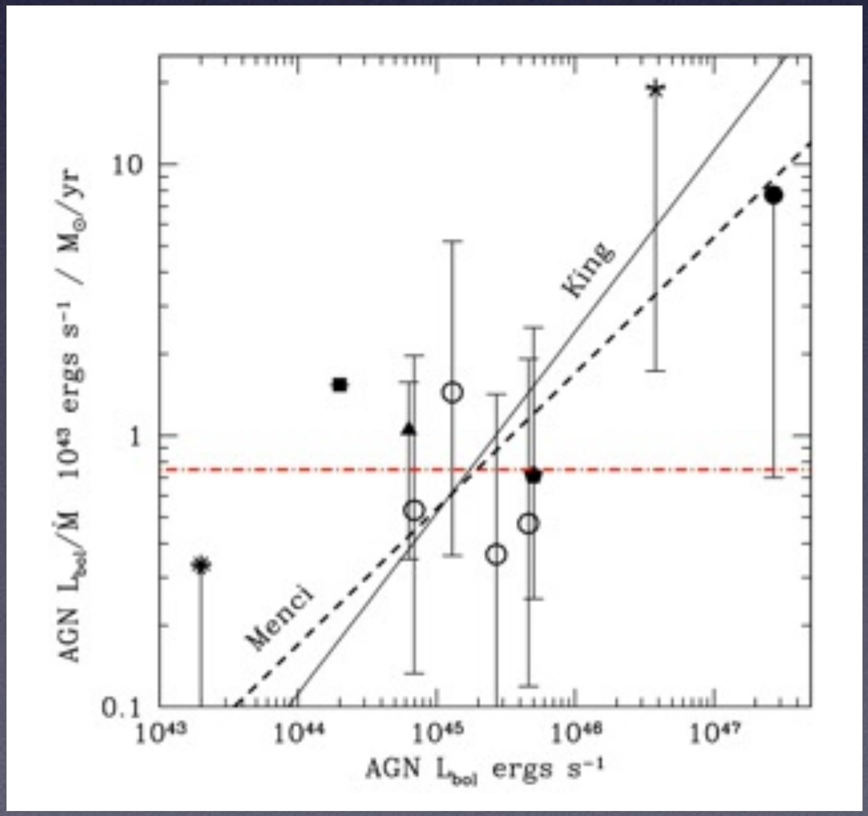
Herschel/PACS results + IRAM : statistics

1 -Fast OF occurr in the late merger phase ULIRG/QSO
2- driven by AGN
3- Velocity (OH) correlated with 9.7 um sylicate absorption (Spoon+13)

Location, geometry, detailed mapping still needed



L(AGN) /Lsun Veilleux+13



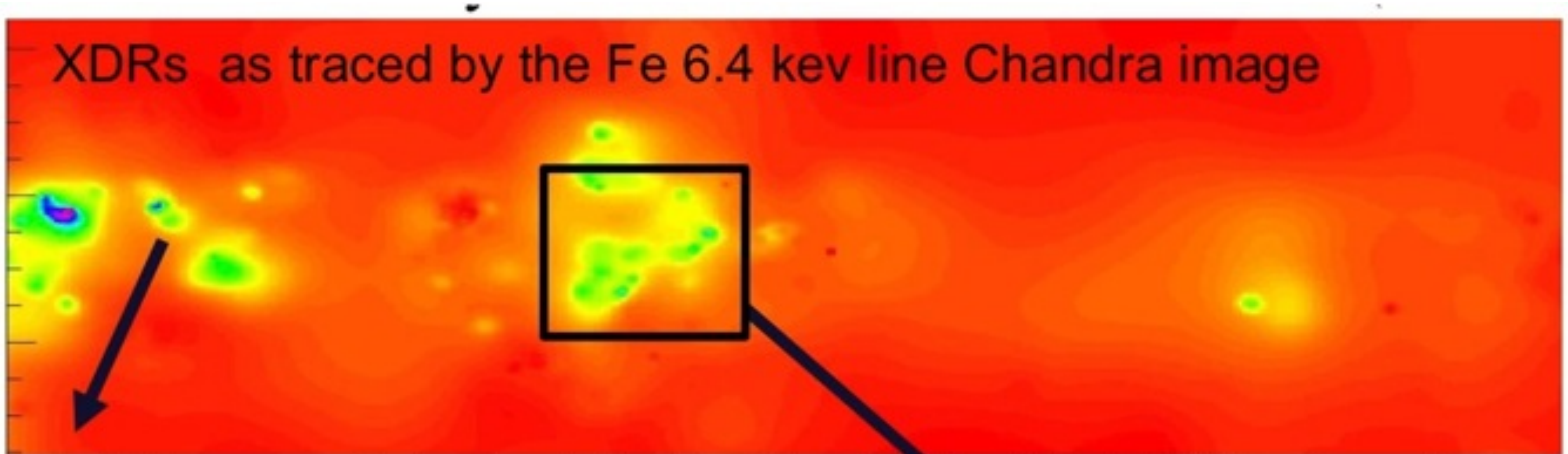
Remarkable correlation between AGN outflow rate and AGN bolometric luminosity:

$L_{bol}/M_{out} \sim 7.5\times10^{42}$ erg/s / $M_\odot$/ yr

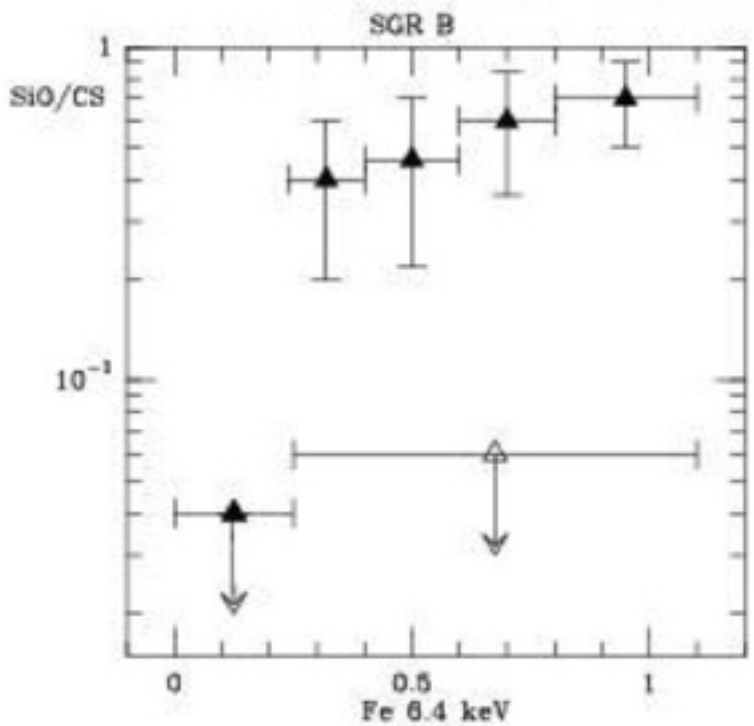
Menci model: $M_{out} \sim L_{bol}^{0.5}$

King model: $M_{out} \sim L_{bol}^{1/3}$

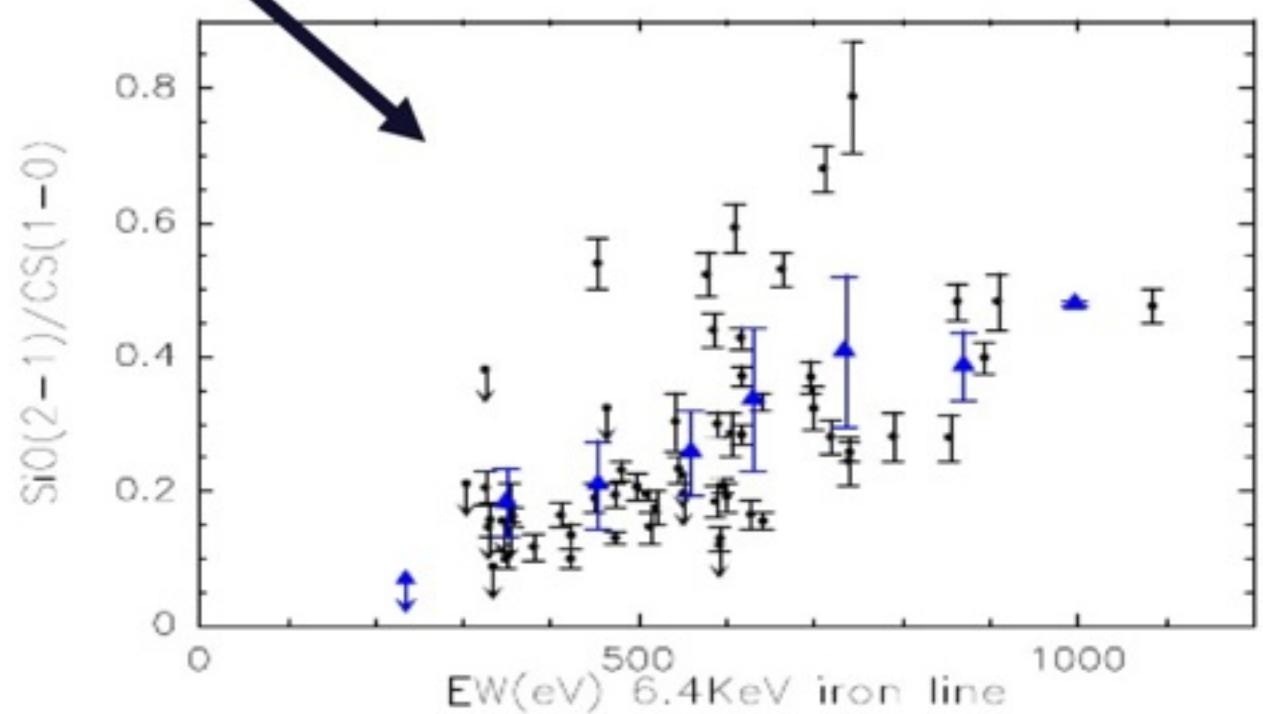
Chemistry of AGN outflows



SiO/CS correlated with the Fe 6.4 keV. XDR chemistry?



Martin-Pintado et al. (2000)



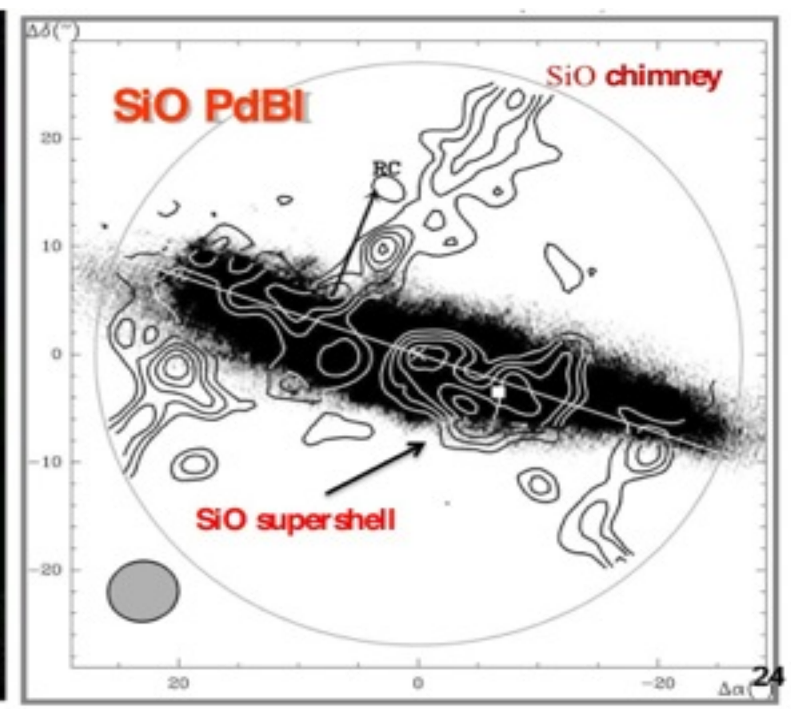
Amo-Balandron et al. (2009)

Feedback, shocks

SiO emission (shock tracer) is out of the plane in M82 superwind :
superwinds expand by shock
- Traces the walls of the supershells - not the SF regions
- Vertical filament - SiO chimney

Also Methanol ~ water on dust grains + shocks

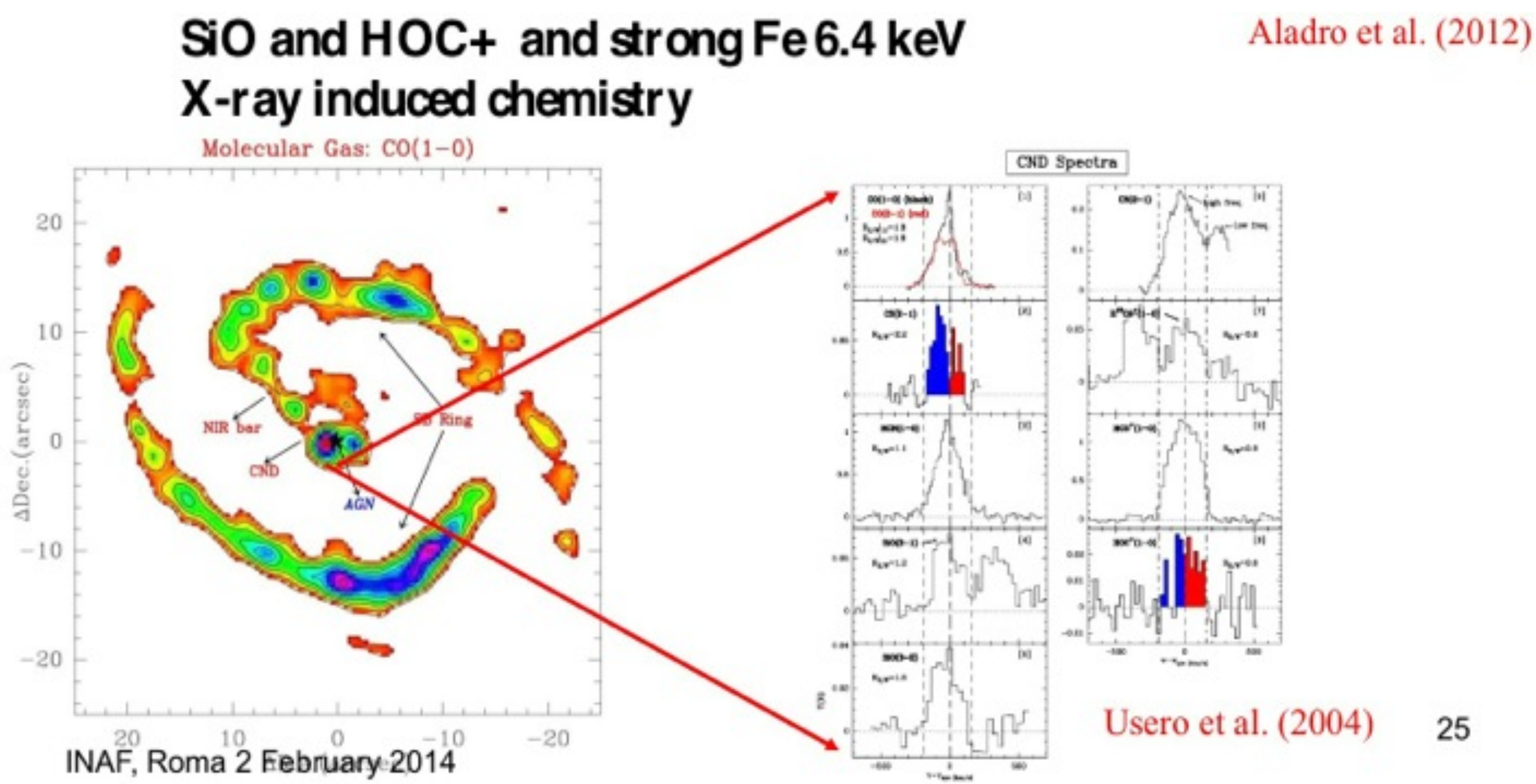
Noema/ALMA will image shocked regions in many AGN and SF galaxies



Other shock tracers:
- **Methanol OK from ground**
- **H2O : only from space for nearby sources**

X-ray induced chemistry - AGN diagnostic

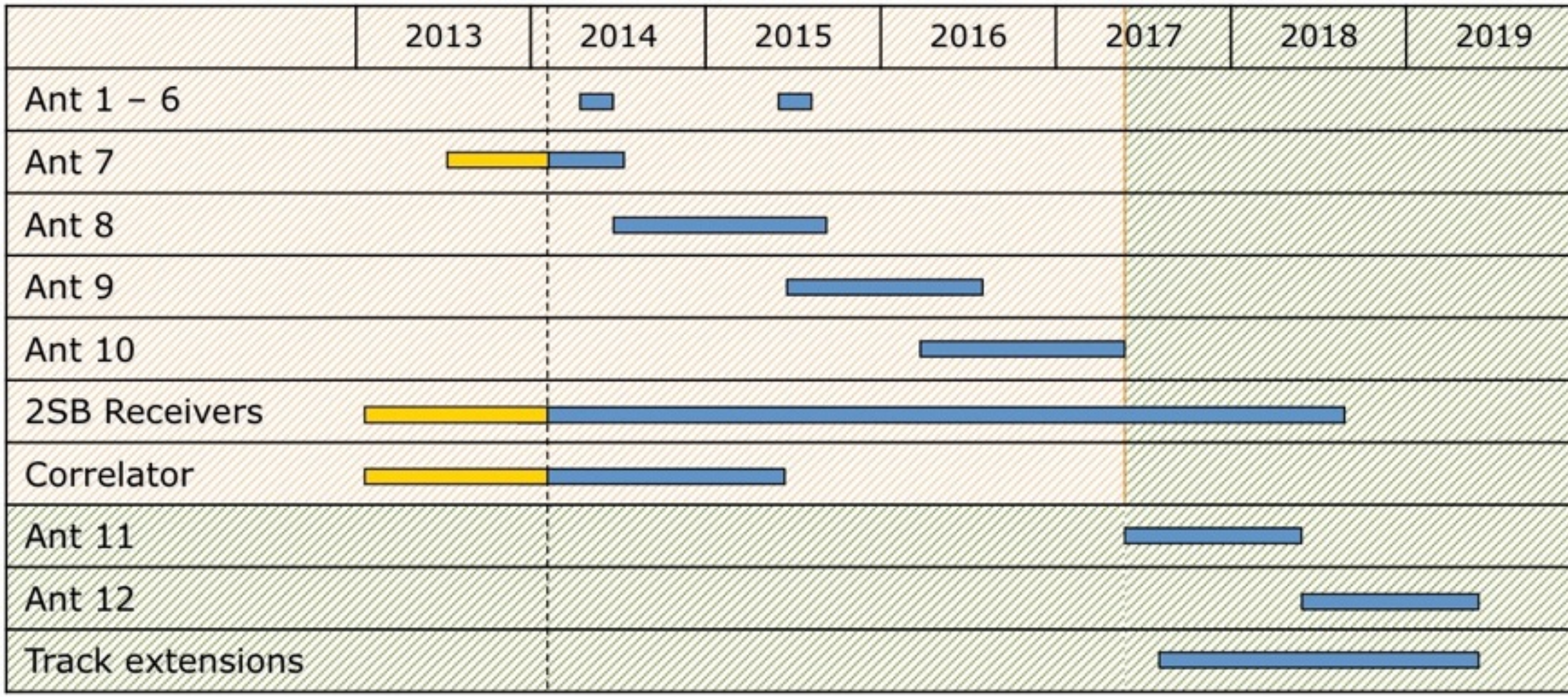
NGC1068



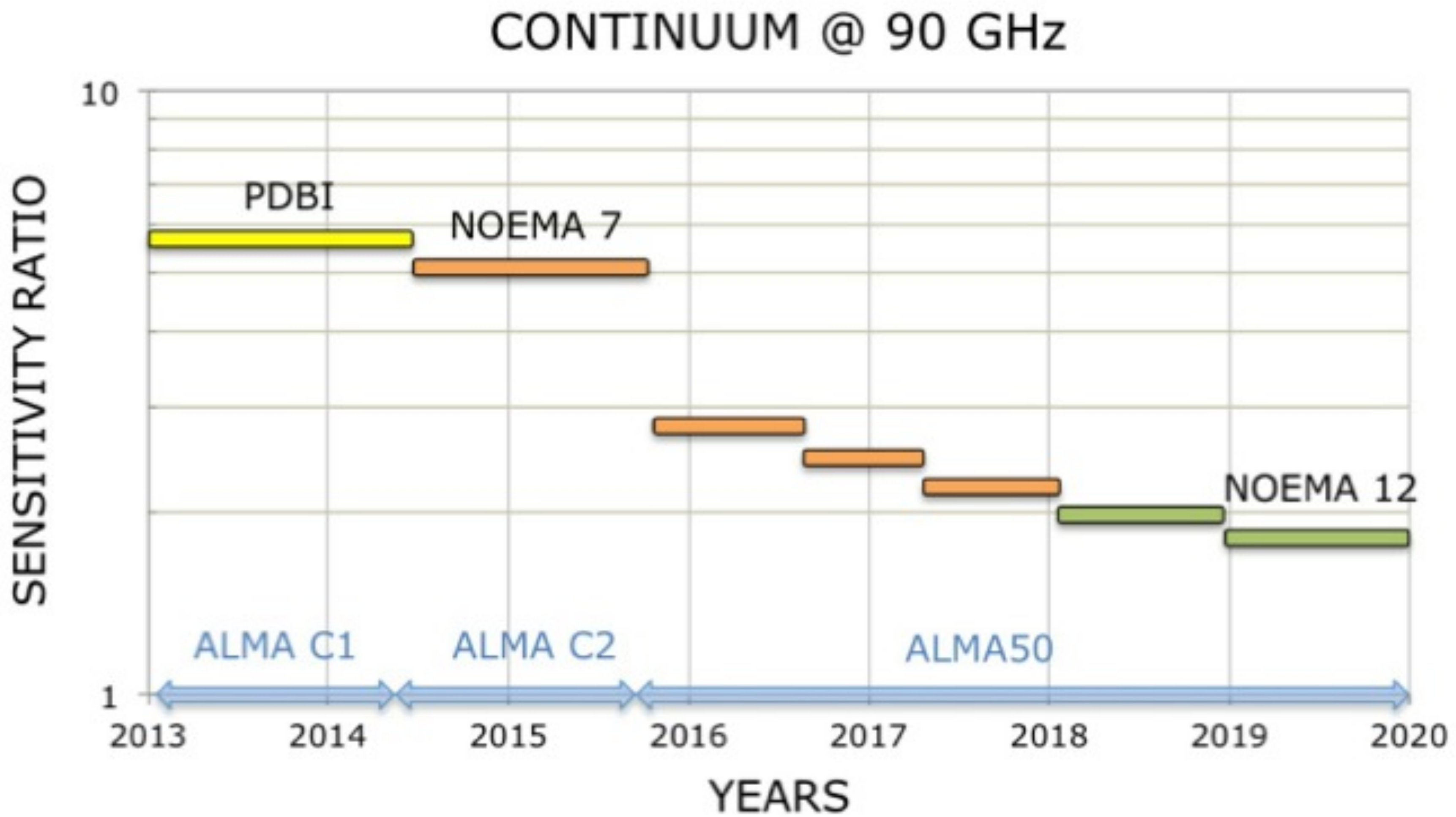
The other way round: **select obscured AGN by molecular tracers**
--> then confirm with ATHENA deep observations

NOEMA The northern Extended millimeter array
Project Summary

NOEMA global timeline



NOEMA: sensitivity @90 GHz



ALMA/NOEMA	SS14	WS14/15	SS16	WS16/17	SS17	SS18	SS19
SENSITIVITY	5.7	5.1	2.8	2.5	2.2	2.0	1.8
SPEED	32.4	26.3	7.8	6.1	4.9	4.0	3.3

Factor of 2 sensitivity w.r.t. ALMA50 at 3mm continuum

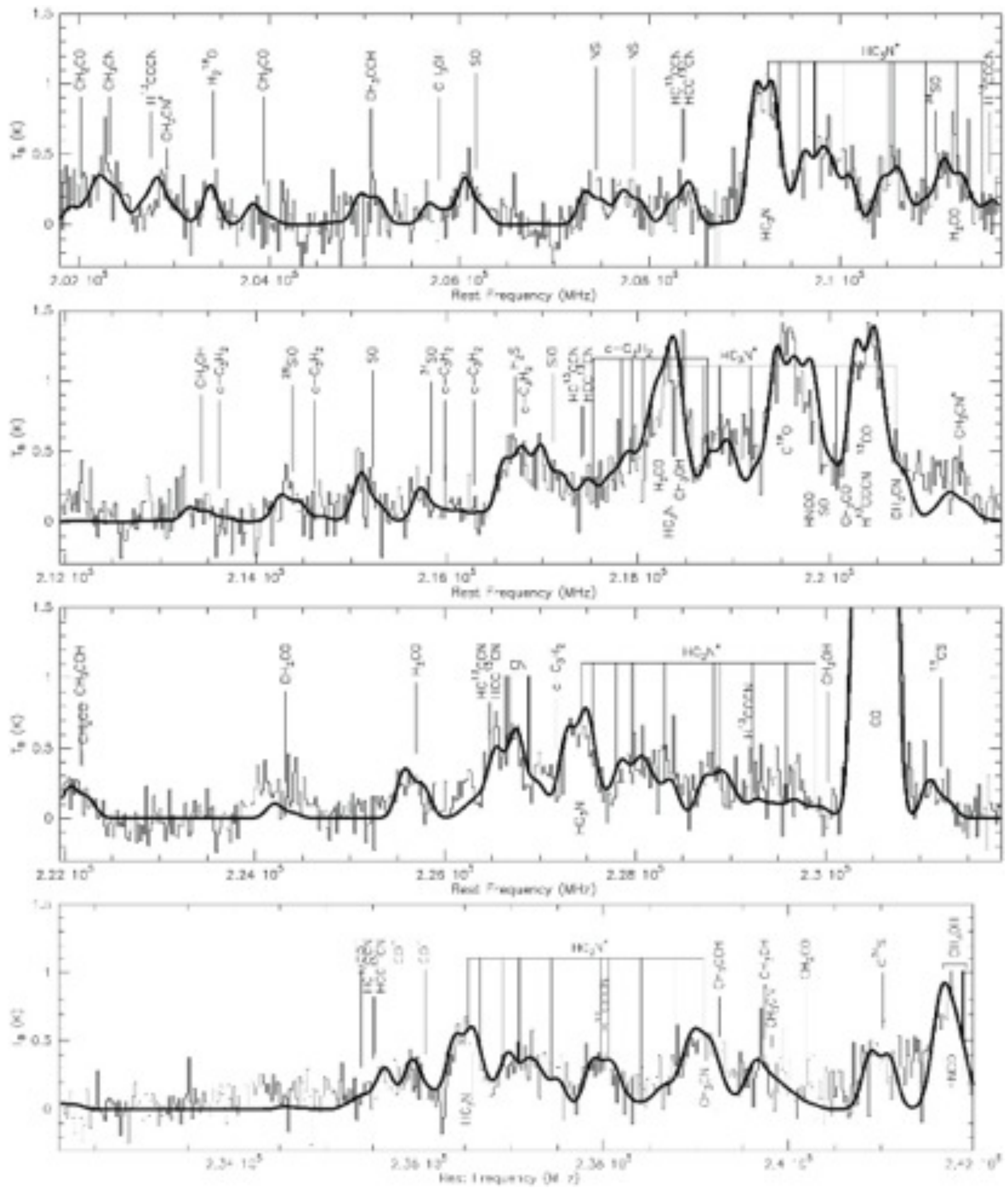
NOEMA ~4x PdBI sensitivity increase in the continuum
~2.3x PdBI sensitivity increase in the line

NOEMA spatial resolution

Source	Distance	Frequency		
		115 GHz	230 GHz	345 GHz
GG Tau	140 pc	60 AU	30 AU	20 AU
NGC 1333	300 pc	130 AU	65 AU	43 AU
M31	700 kpc	1.5 pc	0.7 pc	0.5 pc
z = 1	1.66 Gpc[a]	3.5 kpc	1.7 kpc	1.2 kpc
z = 4	1.46 Gpc[a]	3.0 kpc	1.5 kpc	1.0 kpc

[a] the angular size distance assumes a flat $\Omega_M = 0.27$ Universe.

Spectral surveys with 16 GHz bandwidth
Redshift searches

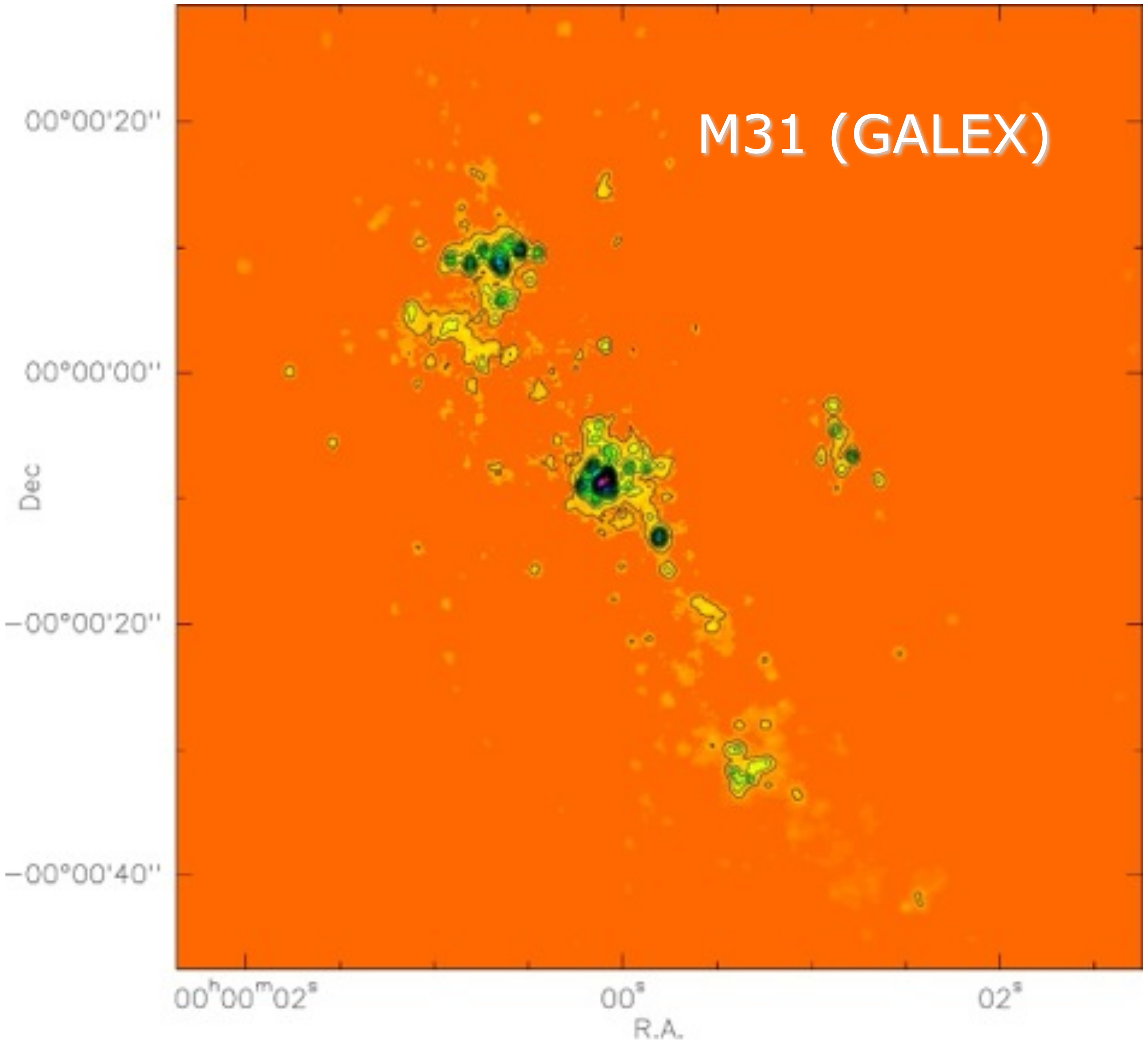


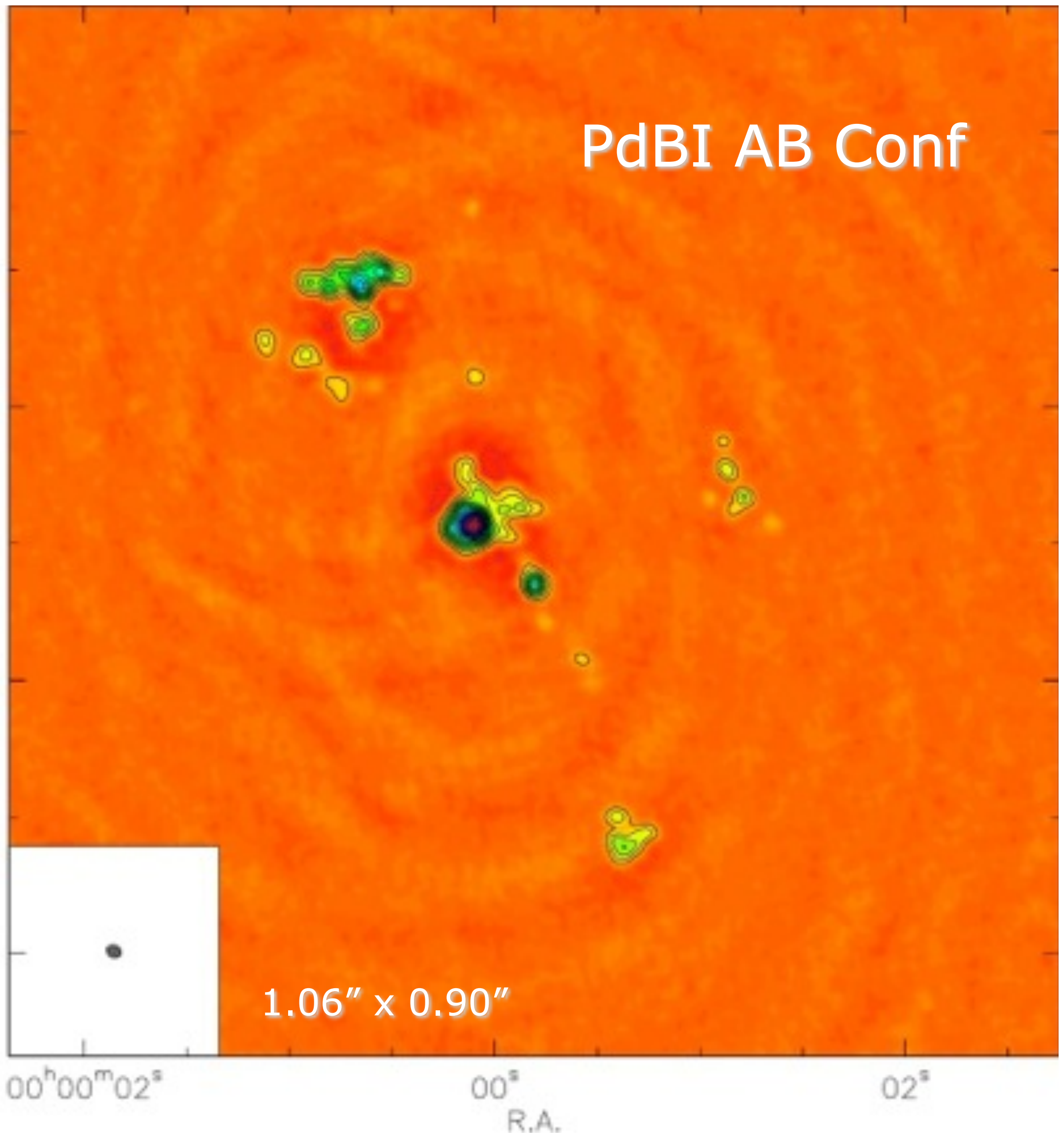
Arp220
Martin+2011

→ Systematic studies & surveys that ALMA will not conduct now

Imaging ⟹ Simulations @ 100 GHz

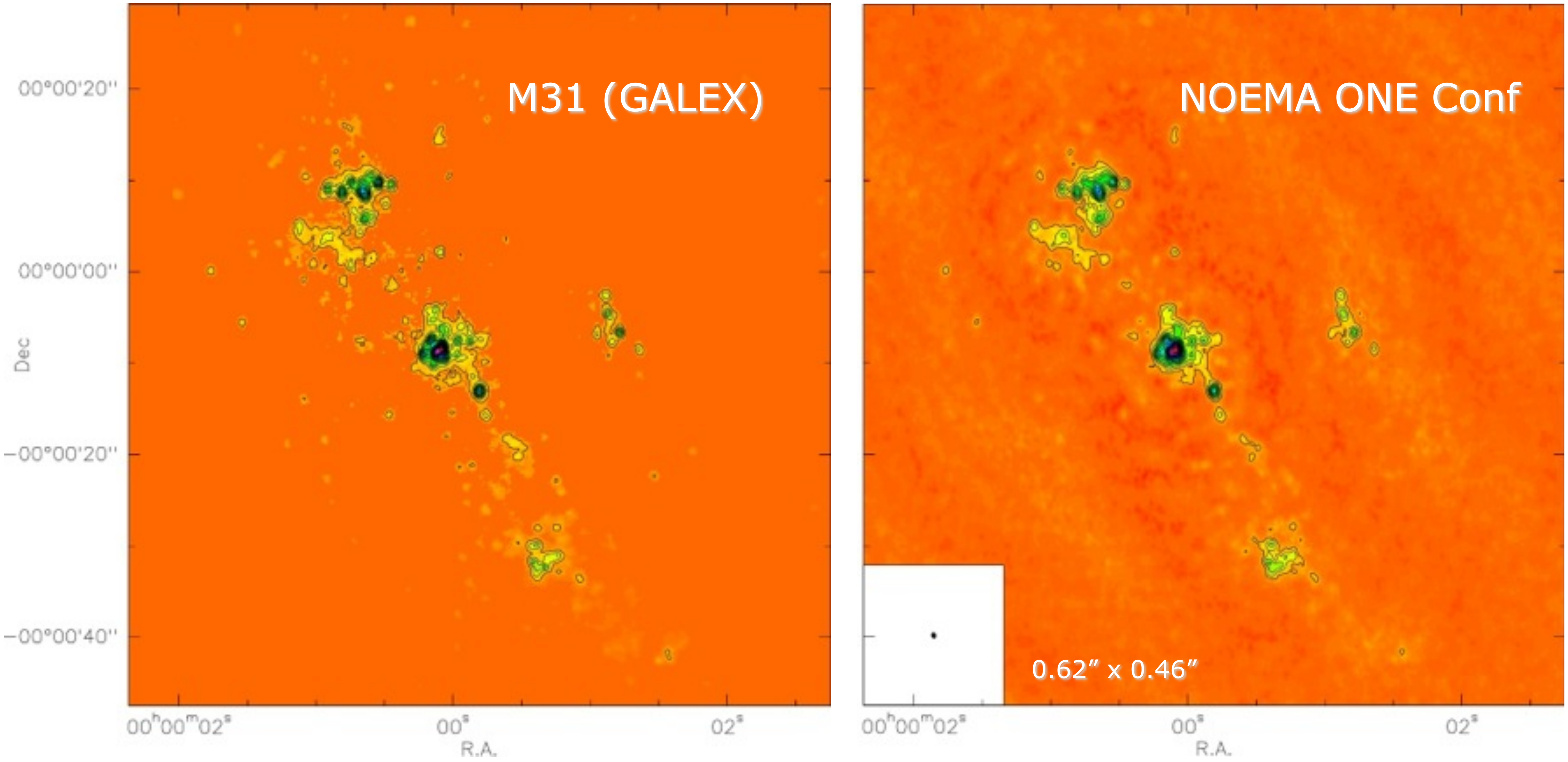
Boissier 2009





Imaging ⟹ Simulations @ 100 GHz

Boissier 2009



Conclusions

What we learnt:

- Molecular outflows common in ULIRG/QSOs , massive & powerful
- Maximum in the late-merger ULIRG/QSO phase
- High velocity + Herschel suggests that the outflow is driven by AGN through shocks (H2O)

What's next?

Local galaxies:

- Morphology/geometry of galaxy wide outflows

- Assess whether the outflow is driven by a shock,

understand the energy transport mechanism from the nucleus to the disk

z=2-3:

- How common AGN feedback at the peak of

galaxy/AGN evolution, z=2-3? and beyond

- In which phase of host/AGN evolution does AGN feedback start to be active and how long does the active phase last?

How?

CO,HCN,.... NOEMA/ALMA
CII from SPACE

Shock tracers: SiO, methanol, ... NOEMA/ ALMA
+ H2O from SPACE only

Spatially resolved nea-ir and mm spectroscopy
Sinfoni/VLT, NOEMA, ALMA, E-ELT
SKA - HI 21 cm line

Observe large samples/surveys